# *Development of a Stochastic Based Multidimensional Matrix for the Analysis of Pavement Performance Data*

A thesis submitted in partial fulfilment of the
requirements for the Degree

of Doctor of Philosophy in Civil Engineering

in the University of Canterbury

by Jacobus Daniel van der Walt

University of Canterbury

2017

---

Supervisor: Dr E. Scheepbouwer

Co-Supervisor: Dr B. D. Pidwerbesky

# Abstract

As pavement condition becomes an ever-growing problem within the ageing New Zealand road network, a challenge emerges to effectively analyse the ageing pavement databases to improve pavement performance. Establishing how the various factors affect pavement performance is complicated due to the random features of pavement deterioration and the complex relationships between different parameters. To address this, it is proposed that a new tool be developed that will combine critical indicators into one structure for performance comparisons. The tool takes the form of a stochastic multidimensional matrix which can deal with random features and complex relationships. The range of pavement technologies that will be compared is based on data available within the New Zealand Long-Term Pavement Performance database (LTPP). The data is collected by professionals with industry standard or better equipment for New Zealand conditions.

This research found a possible weak point in data quality. The location with respect to the wheel path of where the data was collected is estimated to the best of an engineer's ability and not measured directly. If data was not collected in the wheel paths, allowances must be made. This research presented a new methodology to check and quantify the wheel paths distribution. Deploying this methodology on an LTPP test section showed that the estimation method employed by the NZTA was sufficient and no allowances had to be made to the data. This research also highlighted that the wheel path width is not as wide as originally anticipated for both light vehicles and heavy vehicles. This information was shown to be valuable for contractors in calibrating the variable bitumen spray bar.

Once the validity of data was established, the data structure and selection methodologies were investigated. From the literature review and discussion with experts, a multi-dimensional approach was chosen. This approach allowed for multiple

levels of research to be conducted. Data could easily be analysed at a site, indicator or network level all within one structure. As the databases were large, the multi-dimensional structures would be filled with stochastic indicators rather than storing the entire population. This allowed for two key advantages; firstly, it allowed the structure to remain small and easily manipulated. Secondly, it allows most computational power to be conducted up front. Therefore, allowing researchers to establish trends much more quickly by simply examining the multi-dimensional structure in different dimensions.

The comparison of different indicators to identify sections of pavement that are performing well was the next objective. This involved the featurization of pavement data through the use of fuzzy logic and combining the featurization data with expert weights. This allowed different sections of pavement to be ranked and establish which pavement sections were performing well. This research presented a new method of establishing fuzzy memberships functions based on data and not on expert opinion. This research established a new tool called The Stochastic Based Multi-dimensional Matrix (SBMDM).

This research will present two examples of how the SBMDM was demonstrated through case studies. These case studies investigate pavement performance for a specific location and investigate the SBMDM at a network level. After interviewing experts in New Zealand through the implementation of the Delphi method, it became apparent that rutting is the most important pavement performance indicator for New Zealand roads. By adopting this point and utilising the SBMDM, an in-depth study was completed on LTPP sites in the Canterbury region. Results show that there is a significant difference between the LWP(outside) and RWP(inside) rutting. This research reasoned that the camber or cross fall of the roads surface, caused an uneven distribution of load, resulting in the observed results.

The second study used the SBMDM to analyse rutting from a network level. The results show that there is a significant difference in the amount of rutting in the inside wheel path compared to the outside wheel path. Using deterioration models developed in New

Zealand, it was shown that the models matched the trend seen at the network level. From this result, it can be reasoned that there is a deterioration cost due to camber.

The research includes a comprehensive literature review. Each chapter will include further detailed literature as it relates to a specific topic. The scope, objectives, methodology, results, recommendations, and conclusions of the research are also detailed.

**This research includes components from the following journal papers and presentations:**

## Accepted journal papers

J.D. van der Walt, E. Scheepbouwer & S. L. Tighe (2016): Differential rutting in Canterbury New Zealand, and its relation to road camber, International Journal of Pavement Engineering, DOI: 10.1080/10298436.2016.1208198

J.D. van der Walt, E. Scheepbouwer & N. West (2017) Positioning of travelling vehicles in rural New Zealand on chip sealed roads, Journal of Structural Integrity and Maintenance

## Journal papers submitted and in review

J.D. van der Walt, E. Scheepbouwer, B. Pidwerbesky & B. H.W.Guo (TBA) Rut depth prediction and its relation to camber for chip seal over granular base pavements.

J.D. van der Walt, E. Scheepbouwer, B. Pidwerbesky & B. H.W.Guo (TBA) Muti-Dimensional, fuzzy selection support tool to repeat pavement success.

## Accepted conference papers and technical presentations

J.D. van der Walt, Development of a selection support tool (2015), Presented at: The National Pavements Technical Group, Christchurch, New Zealand.

J.D. van der Walt, E. Scheepbouwer & N. West (2016) Lateral position of vehicles in the Canterbury region, Presented at: Washington D.C, Transportation Research Board Business Office

J.D. van der Walt, E. Scheepbouwer, B. Pidwerbesky & B. H.W.Guo (2017) Deterioration cost due to camber for chip sealed pavements over granular bases, Presented at: 2017 Maireinfra, Seoul South Korea.

# Contents

List of Figures

List of Tables

# Comments on thesis structure

The body of work of this thesis is structured as follows. Each chapter is an individual and self-contained part that can be read without requiring knowledge from other chapters. However, as a whole, the chapters also form the narrative of the research journey. To facilitate this, each chapter begins with the title, 'The purpose of this chapter,' where the relation of the chapter is explained in the broader context of the body of work.

# Chapter 1 Introduction, Review and Goals

# Purpose of this chapter

This chapter provides the background for the undertaken work. It elaborates on the research need and answers the question, ‘why has this research been undertaken.’ A broad literature review establishes the context for the research, leaving more specific reviews to be discussed in following chapters. The chapter will result in the establishment of the overall research goals, scope and present the people who mentored this research throughout its development.

## 1.1. The need for research

In recent years the New Zealand Transport Agency (NZTA) has spent in excess of two billion dollars on land transport infrastructure per year (NZTA, 2014). However, according to the NZTA State Highway Asset Management Plan 2012-2015 (NZTA, 2011), this amount is not adequate to preserve the current service level of the network. Therefore, there is a need to decrease the life cycle cost through the development of more effective asset management tools. The performance of different pavement technologies is one of the most critical aspects of an asset management system, and it has become ever more complicated. Where in the past, the choice for a chip seal only demanded a choice in chip size, nowadays many different seal types have become available (NZTA, 2005).

The NZTA (NZTA, 2015b) has identified the following need in 2015, “The Long-Term Pavement Performance (LTPP) monitoring project has been recording condition information for numerous pavements throughout New Zealand since 2001. While there have been many research projects that have utilised aspects of the collected data, interpretation of the entire database has not been attempted, nor have any studies utilised data from the last few years.”

To address this need, this research proposes that a stochastic based multidimensional matrix (SBMDM) is developed that will aim to utilise the LTPP database and combine all critical indicators in one system for accurate performance analysis.

## 1.2. General background literature review

### 1.2.1. Background of pavement management systems (the 1950s)

Most experts agree that the pavement management system(PMS) started with the development of standardized pavement tests first introduced by American Association of State Highway and Transportation Officials (AASHTO). The study is now commonly known as the AASHTO road test and was carried out in the late 1950s. Researchers determined that a universal test was needed that would indicate the road deterioration which was independent of pavement type and construction methods. As the study progressed, they determined that a road test based on serviceability or “ride comfort” would be the most universal. AASHTO researchers faced a problem of how to determine ride comfort without having to ride over every section of pavement in the network. The first step was selecting a group of individuals, and then ask them to drive over predefined sections of pavement. They were asked, without looking at the pavement but only based on ride comfort, to rate the pavement on a scale from 1-5. This rating was called the Present Serviceability Rating (PSR). After the test was complete, they would then also have to answer a question, “How do you feel about driving over the rated section for a long period or long distance” – "would it be acceptable or unacceptable?” The next stage was to record all of the pavements’ physical failure modes. This included fatigue cracking, longitudinal cracking, rutting, roughness, number of patches and the amount ravelling. Correlations were then made between the average PSRs and the physical measurements. This correlation is called Present Serviceability Index (PSI). Carey and Irick showed that about 95 present of the serviceability data for pavement is contributed by the surface roughness profile (Carey & Irick, 1960). The other failure models were found to be statistically significant, however, only contributed to about five present of influences to serviceability. The results of this work remain central to PMS all around the world. Presently the International Roughness Index (IRI) is used to estimate network deterioration in New Zealand. IRI will be one of the key indicator used in this research. It must be noted, however, with the advances of high-speed testing technology and roadway imaging, asset managers have moved away from IRI as their primary triggering factor (however it is still very significant) for the commencement of maintenance. They now rely on the detection of other more localized pavement distress mechanisms (Minnesota-DOT, 2007).

### 1.2.2. Incorporation of asset management framework in New Zealand

In New Zealand, a traditional Pavement Management System has not been used by its highway agency for at least 15 years. Instead, New Zealand Transport Agency (NZTA) has moved to a framework where asset management principles are applied to obtain funding for transportation infrastructure. This asset management framework also incorporates full life cycle cost analysis and sustainability principals (Bryan Pidwerbesky, 2015).

Asset management ideology has developed in New Zealand for several reasons. Firstly, by law, the central government requires all government agencies to value the national assets under their jurisdiction. This means that the New Zealand highway agency must evaluate its entire network in terms of replacement cost and depreciation annually. Secondly, an association of national and local representatives was formed in 1995 called the National Asset Management Steering committee (NAMS). NAMS as a group aims to enhance the well-being of

New Zealanders through the leadership of asset management (NAMS, 2015). They have been hugely influential in promoting sustainable asset management locally and internationally through publications and training (Geiger et al., 2005).

One of the main disadvantages with the traditional PMS was the cost and effort involved to collect masses of data and not having much to show for it in terms of usable information (Bryan Pidwerbesky, 2015). In light of this, in 2001 NZTA invested in the LTPP program which has a focus on accuracy. This research will help utilise this data and bring meaningful information to industry to support the asset management culture in New Zealand.

### 1.2.3. Long-term pavement performance program background (the 1980s)

The original LTPP program started in the United States of America with the introduction of the 1987 Highway Act. With this Act Congress then authorized the Strategic Highway Research Program (SHRP). This program was granted 150 million dollars over five years, and within it, the 20-year long LTPP was designed. After the first five years of LTPP operation, SHRP concluded its responsibilities and the remaining 15 years of the LTPP program was handed over to the Federal Highway Administration (FHWA).

The objectives of the LTPP are outlined below and would later be adopted by other counties DOTs and highway agencies including NZTA.

- Evaluate existing design methods
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements
- Develop improved design equations for new and reconstructed pavements
- Determine the effects of
    - Loading
    - Environment

- Material properties and variability
- Construction quality
- Maintenance level of pavement distress and performance

Originally the program was to include three types of main study areas.

- General Pavement Studies
  - Studies included: Asphalt concrete on bound Base, Asphalt concrete on granular base, Jointed Plain Concrete and Continuously Reinforced.
- Specific Pavement Studies
  - Specific Goals and are performed by experimental approaches
- Accelerated Pavement Testing.

(McComb & Richard, 1988)

The objectives listed above formed the foundation for the development of other Long-Term Pavement Programs around the world including New Zealand's own LTPP.

### 1.2.4. LTPP in New Zealand (the 1990s – 2016)

In the late 1990s, New Zealand started to significantly invest in asset management through the incorporation and development of specific predictive models to forecast long-term pavement maintenance needs within their pavement management plan. Like many countries, the approach included the HDM – III & IV models (World Bank Highway Development and Management Pavement Deterioration Models). Software called dTIMS (Dighton Total Infrastructure Management System) was used with the combination of New Zealand practices and with the HDM model to form a system with predictive capabilities.

From the start, the need to calibrate the HDM models was realized. However accurate New Zealand calibration data was not readily available. Therefore, computer models were used for calibration. In 2001 the New Zealand LTPP program was established to record accurate pavement data for New Zealand conditions. (T.F.P. Henning, Dunn, Parkman, & Brass, 2004):

- In 2001 Transit New Zealand, now part of New Zealand Transport Agency (NZTA), established 63 evaluation sections on the state highways. The conditions of these sections are recorded annually.
- The Land Transport New Zealand, in association with 21 Local and District Councils, established 82 LTPP sections on both urban and local roads (T. F. P. Henning & D. C. Roux, 2008).

The LTPP monitoring sections consist of 300m long sections of roadway that have been selected by a design matrix (developed by T.F.P. Henning & NZTA published in 2008). This matrix ensured that a representative sample was taken from New Zealand roads. This includes sections from different areas, traffic, pavement, climate and network types. On selected sections, no maintenance is allowed other than safety-related maintenance as explained in Appendix B. The remaining LTPP sections are under ordinary maintenance conditions for that particular area/ network. The LTPP data consists of inventory, as-built, traffic, strength, maintenance, and condition data. A summary of the available data is provided in Table 1.

*Table 1 : Review of data available for LTPP sections*

| DATA ITEM | DESCRIPTION | SOURCE |
|---|---|---|
| **INVENTORY** | Pavement layering, material properties, and surfacing | RAMM |
| **RAINFALL** | Rainfall data | NIWA |
| **TRAFFIC** | (AADT) traffic data and the estimated % of vehicle type distribution | RAMM |
| **CONDITION** | Measures condition performance indicators such as texture visual effects rutting roughness. | LTPP |
| **PAVEMENT STRENGTH** | Analysed Falling Weight Deflectometer (FWD) | Yearly/annual FWD Surveys spaced at 50 m intervals |
| **MAINTENANCE** | Maintenance records of the LTPP sections | LTPP RAMM |

(T. F. P. Henning, S. B. Costello, & T. G. Watson, 2006)

### 1.2.5. The ways that the New Zealand LTPP data have been used in the past

Since the creation of the New Zealand LTPP program, many research papers have been published utilising parts of the database. The research generally falls into two categories: deterioration modelling and investigation into a single condition aspect of pavements in New Zealand.

*Deterioration modelling*

The PhD thesis by T.F.P. Henning (2008) focusses on developing pavement deterioration models for the New Zealand state highway network. As part of this research, the New Zealand LTPP program was established. This research gives valuable insight into how LTPP sites were assigned and the reasoning behind the experimental design (T. F. P. Henning, 2008). After the inception of the LTPP program, research was conducted to test the current pavement deterioration models adopted by New Zealand. The majority of these models were adopted from HDM, but some locally developed models were also tested. Key areas of their research and methodology will be of importance to this work (T. F. P. Henning et al., 2006).

Further work was conducted on the Adjusted Structural Number (SNP) which the current pavement deterioration models in New Zealand rely on. The SNP is expected to describe the performance of a multi-layer system and its deterioration as part of the HDM-4 model. Stevens D., Salt G., et al., proposed that in many cases structural distress can be allocated to one or more of at least four discrete categories: rutting, roughness, crack initiation and shear instability. They proposed that SNP be replaced by four structural indices that they have developed. The work done by Stevens D. Salt G. et al. (2009) has highlighted possible performance measures to be included in the SBMDM (Stevens, Salt, Henning, & Roux, 2009).

*Investigation into condition aspects of pavements In New Zealand*

More recently, research has been conducted on condition aspects of pavements in New Zealand. Kodippily, Henning, and Ingham (2012) researched pavement performance data (LTPP) to determine the combination of factors that provide the best indication of flushing occurrence on in-service pavements. Regression analysis of the combination of these factors gave a model to identify flushing. They identified that dry density and water content have a significant effect on flushing (Kodippily, Henning, & Ingham, 2012). Following this, further work was done on pavement failure. There is an unknown risk of failure due to the variability in design, materials and differing environmental conditions. This paper takes a diagnostic approach to developing a model that highlights the importance of having a comprehensive understanding of the underlining cause of failure (Schlotjes, Henning, & Burrow, 2012). The outcomes of this research are valuable in determining underlining relationships in the data where correlation does not equal causation.

*Discussion*

This research will investigate the database from a holistic view. This proposed research seeks to take a “performance snapshot” of the currently available data for analysis. Aspects of previous research will be used to help understand the context and features of the databases as mentioned in the previous section.

From the literature review surrounding the LTPP database, it can be noted that there is no one tool that analyses pavement performance using the majority of the LTPP database. The analysis of the LTPP database using stochastic multi-dimensional matrices has also never been done.

### 1.2.6. RAMM database overview

RAMM is a software suite that provides pavement assessment and maintenance management to government agencies, consultants, and contractors (RAMM, 2014). The RAMM database contains the following information at a treatment level to help determine pavement performance:

• Presence of flushing using model developed by Kodippily, Henning, and Ingham (2012)

• Premature failure: RAMM can report on the expected seal life at a generic level. RAMM also contains data for each reseal where the ‘expected life’ field has been updated.

• Reduction in texture depth: when texture depth reduces by 0.3 mm per year or more between annual high-speed data surveys.

• Shortening reseal cycle: treatment lengths are flagged by RAMM where the life of each successive reseal is reducing.

• Flushing before the last reseal: interpreted from historical surfacing and condition data.

(NZTA, 2005) (RAMM, 2014)

### 1.2.7. Review of pavement structures

Flexible pavements consist of layered material over the in-situ or imported subgrade soil. The surface layers are exposed to higher, environmental and traffic (load) stress concentration than lower layers as shown in Figure 1. The upper layers must be constructed with higher quality control in mind. Figure 1 shows the two layers of different materials below the surface layer called the base course and sub-base. Ideally, these two layers could be constructed with the base course material however due to the lower stresses it is more economical to use a material with lesser quality and therefore lower price in the sub-base. It must be noted that in practice the pavement cross section may contain more or only some of the layers as shown below in Figure 1 (M. Saleh, 2013).

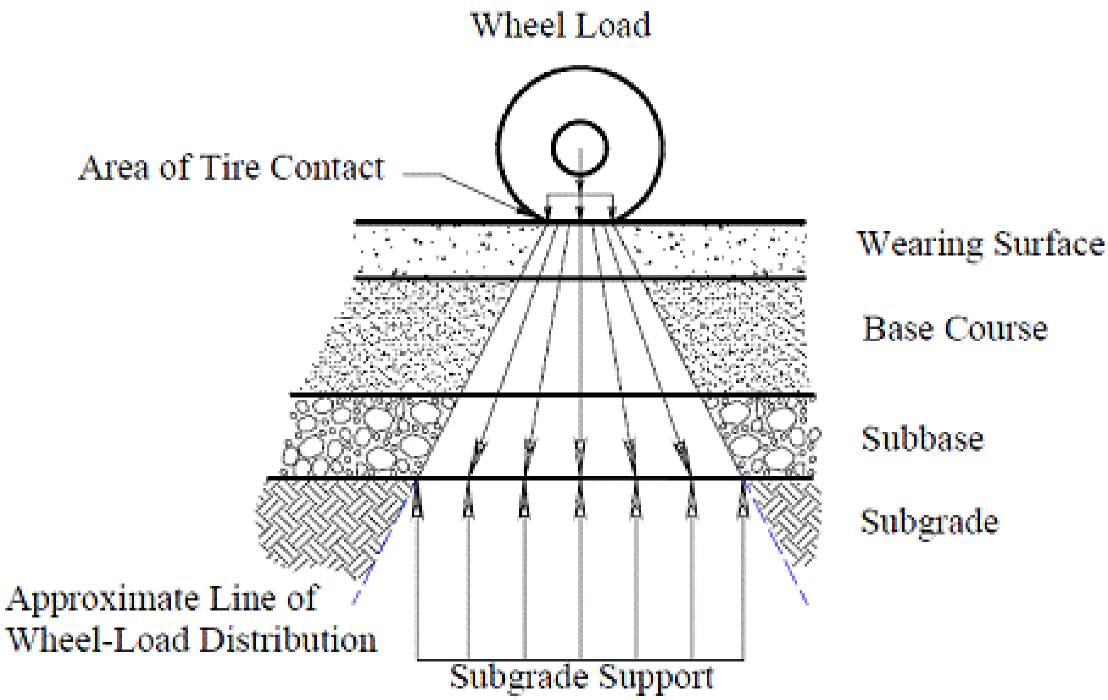



*Figure 1: The pavement cross-section with approximate stress distribution adopted from (The Contractor, 2012)*

### 1.2.8. Traditional factors affecting pavement design and performance

Seven key factors were identified from the literature that affects pavement performance.

1. **Environmental conditions**

Environmental conditions and time of the year play a critical part in the construction of certain pavement technologies (Waters, 2014). Damage is mainly attributable to temperature changes and water infiltration caused by precipitation.

Bitumen is a thermoplastic material; therefore, its properties are greatly affected by temperature. At higher temperatures, the bitumen's resilient modulus is lower, thus explaining why rutting and shoving occur on hot days. The opposite can be said in cold weather; the bitumen stiffens up losing its flexibility and resulting in fatigue cracking.

The amount of rain and snowfall affects the amount of surface water infiltration into the sub-grade and the depth of the groundwater table. Poor management of the access water could bring loss of shear strength, pumping, and loss of support. In extremely cold temperatures and saturated conditions, frost heave can cause differential settlements and pavement roughness (NPTEL, 2007).

2. **Structural models**

Structural models are different techniques in which the pavement structure can be analysed to determine the pavements reactions due to wheel loads. Reactions include stress, strain, and deflections. The most common models are the layered elastic model and the viscoelastic model. The selection of what type of technique is used for modelling can significantly influence the pavement design.

3. **Traffic loading**

Traffic loading is the most influential factor in pavement design/ performance. The fundamental factors include wheel load, contact pressure, axle load repetition of loads, and moving speed of load. All of these factors influence pavement design in different ways but is outside the scope of this study (PavementInteractive, 2007).

4. **Material properties**

The selection of materials and its respective properties are important to pavement design. Material properties must first be specified to conduct analysis to determine reactions such as stresses, strains, and deflections. It is important to note that the selection of material with its respective material properties could be governed by economic analysis and what material is readily available to the location.

**5. Failure criteria**

The identification of failure criteria as set out by the client is extremely important for pavement design. This could include but is not limited to specifications on the skid resistance, fatigue cracking, level of rutting and amount of thermal cracking. The identification of failure criteria which are important to the client may limit the pavement technology able to be used and the materials available to a location. Figure 3 shows common chip seal distress signs as they relate to service level (NPTEL, 2007).

**6. Construction & design time, cost and quality**

Construction period or design period can often dictate what pavement design is viable for a specific context. Frequently, it is not the design and or construction cost that dictates the pavement system, but the cost of traffic management or the inconvenience to the public. In an emergency situation, construction time can become the major driving factor limiting the available pavement systems.(Leslie, 2014). Often it is up to the client to decide what the performance criteria are. Commonly the pavement performance criteria are dictated by one of the following limitations: quality, time or cost (shown in Figure 2).

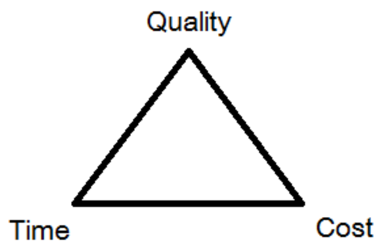



*Figure 2: The time, quality, cost triangle for construction management*

**7. Equipment limitations**

Pavement equipment limitations can influence the selection of pavement system. An example of this would be the foam bitumen machine not being able to pave around sharp corners. The equipment location could make a certain pavement system not feasible due to transportation costs (Leslie, 2014).

### 1.2.9. Review of chip seal technology

Chip seal technology and other similar treatments first became common in the 1920s. The construction is simple in nature, where a layer of bitumen binder is placed and is then overlaid by a layer of aggregate that is embedded by the roller. One of chip seal's purposes is to provide a skid resistant surface on which vehicles can travel on safely. Another is to provide a watertight barrier that protects the base and sub-grade. Traditionally chip seal has been used on only low volume roads; however, with consistent international research done over many decades primarily in the United Kingdom, South Africa, Australia and New Zealand, chip seal has been used on high volume roads with AADT of greater than 20,000. Chip seal is by many still regarded an "Art" despite evidence to the contrary, and for this reason, many international government agencies do not implement chip seals in the pavement management system. This view is due to the traditional qualitative approach with the introduction of McLeod Method in 1970. This method requires experienced personnel to ensure a successful outcome. International research and high way agencies around the world have continued to prove that chip seal can be treated as a highly engineered and technical technology as done traditionally with hot mix asphalt pavements.(NCHRP Synthesis 342 2005)

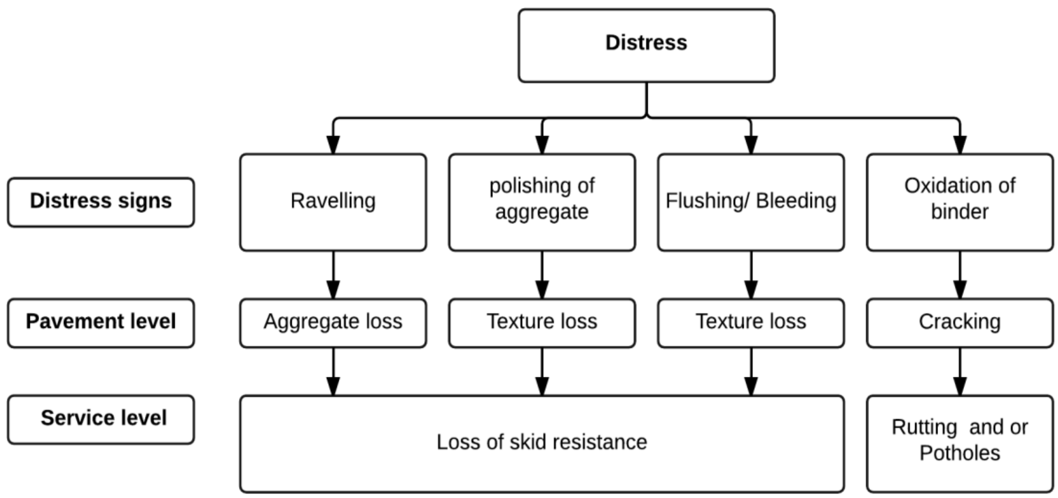



*Figure 3: Chip seal distress model adopted from(NCHRP Synthesis 342 2005)*

### 1.2.10. Chip seals use in asset management

Chip seals have been used in New Zeeland and internationally for many years as part of their asset management plan. The ideal time to apply a chip seal layer is early in a pavement's life before it exhibits a great deal of pavement distress characteristics as shown in Figure 4. This should all be done within an asset management context (Wade, Desombre, & Peshkin, 2001).

*Figure 4: Chip seal rehabilitation over hot mix asphalt (Pavement-Interactive, 2011)*

The life expectancy of chip seal is roughly 7-25 years in New Zealand (Bryan Pidwerbesky, 2015). Therefore, it may require several coats to be applied for the pavement to reach its service life. Some professionals that use chip seal as part of their asset management framework believe that it can be used as a stop-gap procedure. They believe chip seal will slow the rate of further deterioration until funds become available for the overlay. However, it is not recommended to use chip seal on distressed surfaces from an asset management point of view. The chip seal will most likely fail earlier than designed and result in higher life-cycle costs in the long run (NCHRP Synthesis 342 2005).

## Chip seal process

Figure 5 shows the recommended process for design and construction. It is important to note that pre-construction activities play a vital role in this process, re-enforcing the idea that chip seals should only be applied to pavements that do not exhibit a great degree of distress.

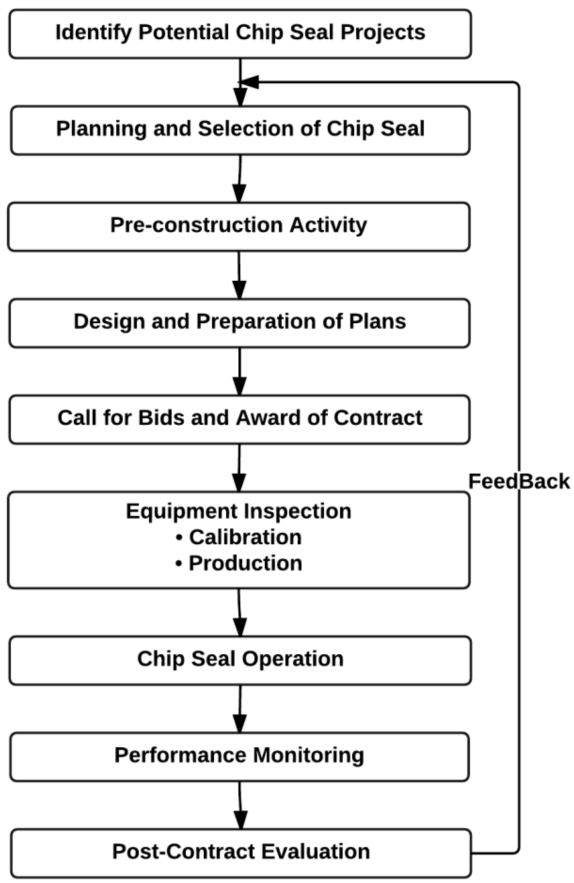



*Figure 5: The chip seal process, adapted from (Senadheera & Khan, 2001)*

Equipment inspection is also important. Factors such as rate of binder and chip application should be tested before starting a chip seal run. Checking that spraying nozzles are operating correctly is critically important. Uneven spraying rates could result in bleeding and or ravelling. (NCHRP Synthesis 342 2005; Sprayed Sealing Guide, 2004)

### 1.2.11. Review of asphalt technology

Asphalt concrete (AC) is a mixture of bitumen and aggregates that form a layer to allow vehicles a smooth surface to travel on. Asphalt concrete is a complex material. The combinations of the temperature/time susceptible viscoelastic properties of the bitumen binder, the environmental effects and stresses due to traffic loads makes AC an incredibly complex system. Fundamentally, AC is made up of two critical components. Firstly, the bitumen binder, a secondary product from petroleum fuel production at refineries. Secondly, the aggregate which is mined from rock quarries, usually closest to the installation site due to high transport costs (Abtahia, Sheikhzadehb, & Hejazib, 2009).

#### Common asphalt mix types

Different traffic and environmental conditions, however, require different combinations of type, size, and proportions of specifically graded aggregate. It also requires careful consideration of type and amount of binder. Finally, the manufacturing and placing will also greatly influence the final product. Careful selection of these factors will allow the final products to provide appropriate levels of structural stiffness, deformation resistance, flexibility, permeability surface texture, and durability. The common asphalt mix types are listed below.

- Dense-graded asphalt (DGA), also referred to as asphaltic concrete(AC)
- Open-graded asphalt (OGA), also referred to as open-graded porous asphalt (OGPA) and open-graded friction course (OGFC)
- Stone mastic asphalt (SMA)

- Fine gap graded asphalt (FGGA)

(Austroads, 2007)

*Environmental impacts*

OGA is considered by experts to be relatively good for the environment. Due to OGA's permeable nature, it acts as a sponge holding contaminants such as heavy metals produced by traffic and keeping them out of the stormwater. Cement concrete pavements are considered to be even better. (Mamlouk, 2014)

### 1.2.12. Pavement engineering viewed as a complex system

*Review of complex systems*

The body of knowledge around complex systems and the use of complex systems are vast (Sanford-Bernhardt & McNeil, 2004). However, there is no single definition of a complex system that all experts agree on (Ladyman, Lambert, & Wiesner, 2012). Here it suffices that a "complex system" is a group or organization which is made up of many interacting parts. In such systems, the individual parts—called "components" or "agents"—and the interactions between them often lead to large-scale behaviours which are not easily predicted from knowledge only of the behaviour of the individual agents" (Mitchell & Newman, 2002). A complex system is a system where there are enough forcing factors that can lead to failure easily, however not enough to cause chaotic behaviour. Therefore some order is still maintained. Lucas (2000) mentioned 18 characteristics of a complex system. An examination of these characteristics by Bertelsen categorized these characteristics into three main groups as shown in Table 2 below (Bertelsen, 2006).

*Table 2: Complex systems characteristics as categorised by Bertelsen (2006).*

| Autonomous agents | Undefined values | Non linearity |
|---|---|---|
| Autonomous agents | Undefined values | Nonlinear |
| Non-standard | Fitness | Emergence |
| Co-evolution | Non-Uniform | Attractors |
| Self-modification | | Phase changes |
| Downward causation | | Unpredictability |
| Self reproduction | | |

*Viewing pavement from a complex system point of view*

Many researchers have noted that pavement engineering and asset management follow many of the key attributes shown in Table 2 (Cheng & Miyojim, 1998; Feighan, Shahin, & Sinha, 1987; Hudson, McCullough, Scrivner, & Brown, 1970; Sanford-Bernhardt & McNeil, 2004).

The known-undefined values and complex relationships from complex systems are commonly assessed through stochastic processes. This is a similar approach taken by this research.

### 1.2.13. Stochastic analysis overview

complex systems like pavement are often analysed through a stochastic approach (example Figure 6). The Oxford Dictionary defines stochastic as, “Having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely”(Oxford Dictionary, 2014).

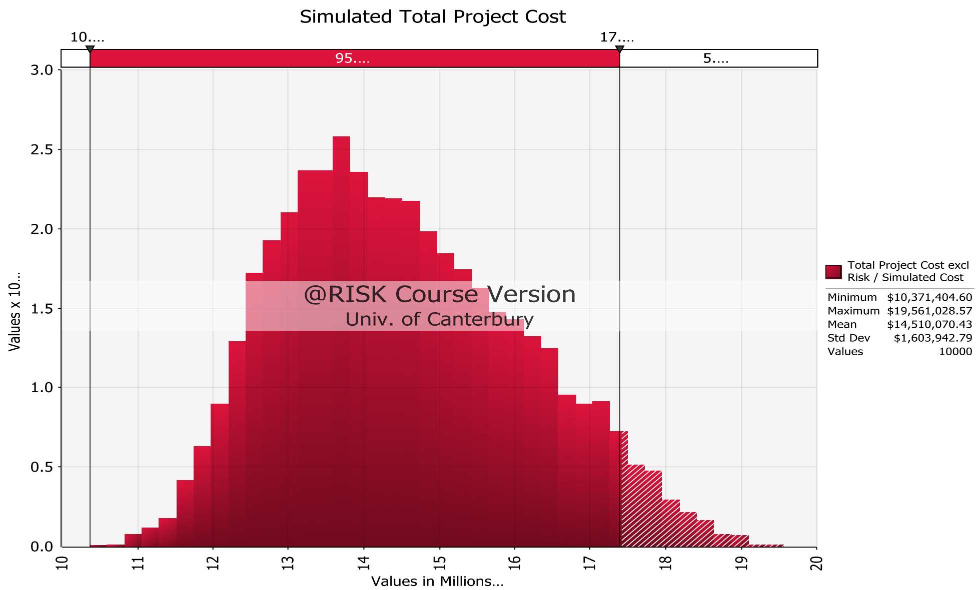



*Figure 6: Example of a Monte Carlo simulation output*

Common tools used in analysing such data are called Monte Carlo and Bootstrap analysis. In a Monte Carlo simulation, uncertain inputs are described using a range of possible value using probability distributions. Common probability distributions include Normal, Lognormal, Uniform, Triangular (example shown in Figure 7), and discrete. A stochastic approach provides many advantages which include:

- Simulation frequently gives improved physical representation of a complex system.
- Easily understood by non-mathematicians.
- Simulation can easily be extended and developed as required.
- Simulation is very flexible. Empirical distributions can be accommodated.

Disadvantages include:

- Calculations take much longer to compute than deterministic calculations.
- Solutions are not exact, and accuracy depends on input data.
- Requires large setup process if an in-depth analysis is required.

(SaRS, 2004)

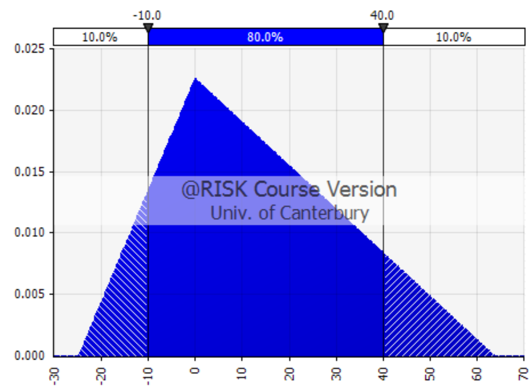



*Figure 7: Example showing a triangular distribution with the following characteristics: a pessimistic value of 40, the best estimate of 0 and an optimistic value of -10 using 10% and 90% confidence intervals*

Note: Stochastic analysis is commonly associated with risk analysis. Risk analysis should always be conducted within the risk management framework like the international standard AS/NZS ISO31000: Risk Management Principles and Guidelines (Standards New Zealand & Standards Australia, 2009).

### 1.2.14. Multidimensional data structure overview

There is a current challenge facing large organizations like DOTs today that is commonly known as data overload. This refers to the sheer quantity of data being captured, at monthly, weekly, daily and hourly levels. With advances in computing, the issue of how to store the overwhelming amount of data has become less concerning than how to effectively analyse it. Multi-dimensional Matrix (MDM), also known as Multi-dimensional Databases(MDD), Multi-dimensional Modelling or Multi-dimensional Arrays in some programming languages, has become an effective tool for analysing large data sets. Each of these has their contextual meaning and differs slightly, but the underlying principles are the same. This approach joined with stochastic attributes, has never been used to analyse the

LTPP database. The advantages and disadvantages of this approach are outlined below. (Colliat, 1996; Laker, 2006; Park & Cai, 2017).

Advantages

- The multi-dimensional matrix transforms the visualisation of a schema into a context focused structure.
- Multidimensional data are implicitly joined, therefore queries that require the formation of joins through hierarchy searches are very fast, as new joins do not need to be established.
- Makes identifying critical relationships easy.
- Easy to identify relationships between different layers of information.
- Every dimension of the matrix gives a different view of the data and can be used for the analysis of a different context.
- The multi-dimensional approach accomplishes period-to-period comparisons by using matrix calculations. Matrix operations can perform calculations on both columns and rows of data in a multi-dimensional environment.

Disadvantages:

- Initially difficult to construct.
- The inert problem where correlation does not equal causation. Therefore, technical understanding the relation between entities is important.
- Outliers can influence many dimensions.

(Matlab, 2014; Oracle, 2006)

In relational data analysis, there is one basic but universal storage structure commonly known as a flat table. The flat table consists of two main parameters called Records (the rows) and Fields (the columns). The flat table can take on many roles depending on how it relates or joins to other flat tables. The role of the flat table can change instantly with the change of context, and therefore it is vital that any flat table is viewed in the right context it was created for. In the multi-dimensional analysis, the same basic underlying structure still exists. However, the way in which they interact is different. To understand simple Multi-dimensional data structures, three terms must be clarified.

**Measurements**

- Table containing context elements
- Fields contain element descriptions
- Referenced by multiple fact tables
- Measures can share dimensions

**Facts tables**

- A facts table is a table containing measurements

**Cubes**

- Cubes are a logical organisation of multidimensional data
- Cubes are derived from fact tables
- Cubes are not exposed to the end-user as they are interested in the measures contained in the cubes
- Dimensions categorise a cube's data, and a cube contains measures that share the same dimensionality

Cubes are extrapolated from fact tables. Cubes contain measures that share common dimensionality, and the measure is linked to a single column from the fact table. Each incorporates context rules directly within its definition (Oracle, 2006).

Calculations within multi-dimensional data can follow matrix manipulation rules. A conceptual example of this is given below in Figure 8 (Matlab, 2014).


*Figure 8: Simple visulization of multi-dimentual matrix multiplication( adopted from oracle, 2006)*

## 1.3. Research objectives

The main objective is to develop a new tool that is capable of extracting information out of large quantities of pavement data.

The secondary objective is to develop a tool that will assist engineers and asset managers with identifying a pavement technology that is performing well.

The proposed tool has the form of a Stochastic Based Multi-Dimensional Matrix (SBMDM).

This research will answer the following questions,

- What are the critical factors influencing the performance that should be included in the SBMDM?
- Can these indicators be accessed from existing database?
- What selection methods are the most appropriate?
- Can this selection model be data driven?

Moreover, provide the following deliverables,

- Construct a robust SBMDM that can analyse the performance of different pavement sections.
- Demonstrate the SBMDM through various studies both at a local level and a Network level.

## 1.4. Scope

The scope of this research focuses on providing a solution to a problem set out by NZTA and industry. The research will focus on New Zealand conditions and pavement technologies implemented in New Zealand. The data provided by the NZTA is New Zealand network-specific, and the tool developed from it will apply to New Zealand conditions. However, the methodology is intended to be universal and may be applied to other parts of the world using respective datasets. The LTPP database is considered by experts as the most accurate information on New Zealand roads currently in the public record and will be the main source of data.

Weather information was gathered from the National Institute of Water and Atmospheric Research Ltd (NIWA). Weather information was collected from the NIWA station located closest to the section of road of interest. No regard will be given to 'microclimates' that may form at certain locations that can result in different weather than what is being recorded by NIWA (Waters, 2014). This is because no more accurate data is presently available for the sections of interest.

From the start, it is important that experts and practitioners have an input in the matrix's development as they may identify potential pitfalls. The research has collaborated with the National Pavements Technical Group, which consists of leading New Zealand pavement designers from contractors, consultants, and NZTA. Their experience and engineering judgment helped as a cross-check of the matrix and its development.

## 1.5. Testing and validation

Testing and cross-validation is a critical part of the research. Without the methods being validated, meaningful conclusions and discussions cannot be formed. This involved the tool being tested with external sources which included engineering judgment from leading experts in the field.

Supervisory steering group:

- **Dr Eric Scheepbouwer –** Director of Construction Management Program, University of Canterbury

- **Dr Bryan Pidwerbesky**–Technical Manager, Fulton Hogan (Large contractor in New Zealand)

External Contributors

- **Prof C. Jahren** - Associate Chair, CCEE Dept.
- **Prof D. Gransberg –** Expert in Construction management and Engineering Costing Iowa State University USA, Adjunct Professor, University of Canterbury
- **Prof S. Tighe** - Norman W. McLeod Professor of Sustainable Pavement Engineering, Director, Centre for Pavement and Transportation Technology and Professor of Civil and Environmental Engineering, University of Waterloo
- **National Pavements Technical Group**, which consists of leading NZ pavement designers from contractors, consultants, and NZTA.
- **J. Waters** - Surfacing Engineer, Fulton Hogan
- **D. Alabaster** - Principal Pavement Engineer, NZTA
- **N. West** - Engineer, Fulton Hogan
- **M. Furguson** – PhD Candidate Stanford, USA
- **Dr S. Paulin –** Tait Electronics, NZ
- **B. Cameron –** PhD Candidate MIT, USA

The SBMDM was validated through multiple research studies using its implementation. The results and development of the SBMDM have also been peer-reviewed by top journals in the field. This research was presented at international conferences to discuss progress and get vital input to the future of the research.

# Chapter 2 Methodology

# Purpose of this chapter

In the previous chapter, a need has been identified for the development of a tool that better utilises current pavement databases. The purpose of this chapter is to present research on the tool's development. This is done from both a holistic and functional point of view.

Firstly, this chapter will review the key milestones in the methodology. This will give a logical framework in which the tool was developed. Secondly, this chapter will present research study outlining the sorting methodologies used. Finally, the chapter will outline the functional implementation structure of the tool.

This chapter has focused on the milestones, holistic details and the flow of information. As the tool contains thousands of lines of code, it is not feasible to explain the programme in detail here.

## 2.1. KEY MILESTONES: Development of the Stochastic Based Multi-Dimensional Matrix

This section presents the key milestones that were required for the development of the Stochastic Based Multi-Dimensional Matrix see Table 3 on next page. An overview of the method is shown in Figure 9.

| MILESTONES | *KEY COMPONENTS* |
| --- | --- |
| 1 Literature review | - Establish need<br>- Overview of research context<br>- Goals<br>- Scope<br>- Deliverables<br>- External contributors |
| **2 Acquire granted access to NZTA RAMM and LTPP database.** | - A crucial part of this research is having access to New Zealand pavement data for analysis. This data was the foundation of the Stochastic-based multi-dimensional matrix.<br>- The LTPP database was the primary focus due to the rigour and accuracy of the data collected within this program. |
| **3 Discussions with experts within NZTA and industry who have researched this area** | - It is important that experts and practitioners have substantial input into the matrix's development.<br>- Experts in the industry have the best understanding of the LTPP & RAMM databases. It was important that they are consulted to avoid common pitfalls. |

| | |
|---|---|
| **4 Preliminary investigation of data Available** | - The LTPP database is strictly controlled by NZTA and their partners and was the basis of this research. Expert consultation and guidance were required to understand all the critical fields within the database.<br>- A preliminary site investigation was completed on one LTPP site utilising equipment called The Infra-Red Traffic Logger or more commonly known by the acronym TIRTL. This investigation compared the position of LTPP testing locations on the road to the wheel path position distribution. For more information see Chapter 3. |
| **5 Identify most critical variables affecting pavement performance and how they are measured.** | Variables investigated included:<br>1. International roughness Index (IRI)<br>2. Temperature<br>3. Pavement condition indicators<br>4. Texture<br>5. Drainage<br>6. Rutting<br>7. Design life<br>8. Life cycle cost<br>9. Duration of installation<br>10. Shoulder size |

| | |
|---|---|
| **6 Data processing and extraction** | - This involved creating a program for sorting and analysing large part of the LTPP and RAMM database.<br>- A custom database was constructed that includes only tables that are of value to the development of the matrix. Due to the restrictions of the RAMM SQL, reading, joining, importing and creating new tables within RAMM is not easy. Only simple queries can run efficiently, and therefore for analytical purposes, the construction of a custom database is the most viable solution. |
| **7 Development of Simple Stage 1 SBMDM** | - - Stochastic based multidimensional matrix with critical variables identified for a limited selection of pavement systems techniques as proof of the technical method that will be developed.<br>- The stage 1 matrix was a bare-bones structure which includes only a few pavement techniques. This matrix was a proof of technical method and gave indications on how to progress to the stage 2 MD-matrix.<br>- This Matrix was not complicated and incorporated limited data.<br><br>*Testing/ comparing/ refinement of stage 1 MD matrix*<br><br>- Preliminary cross-validation from sources outside LTPP database of the SMBDM is crucial. The matrix methodology was cross-checked by professional groups, practitioners.<br>- Stage 1 Matrix conclusion was developed. |

| | |
|---|---|
| **8 Development of Stage 2 – SBMDM with a range of pavement systems included within LTPP.** | Following the lessons and conclusions from the construction of the stage 1 SBMDM, the stage 2 SBMDM was developed.<br><br>*Testing and comparing stage 2 Stochastic Based Multi-dimensional Matrix.*<br><br>- Investigate the advantages and disadvantages of the stage 2 matrix.<br>- Conduct investigation of stage 2 model with reference to New Zealand case studies as discussed with Industry experts. ( see Chapters 4-5) |
| **9 Deliverables/ Conclusions** | - Main findings<br>- Discussion<br>- limitations and advantages<br>- Further work |

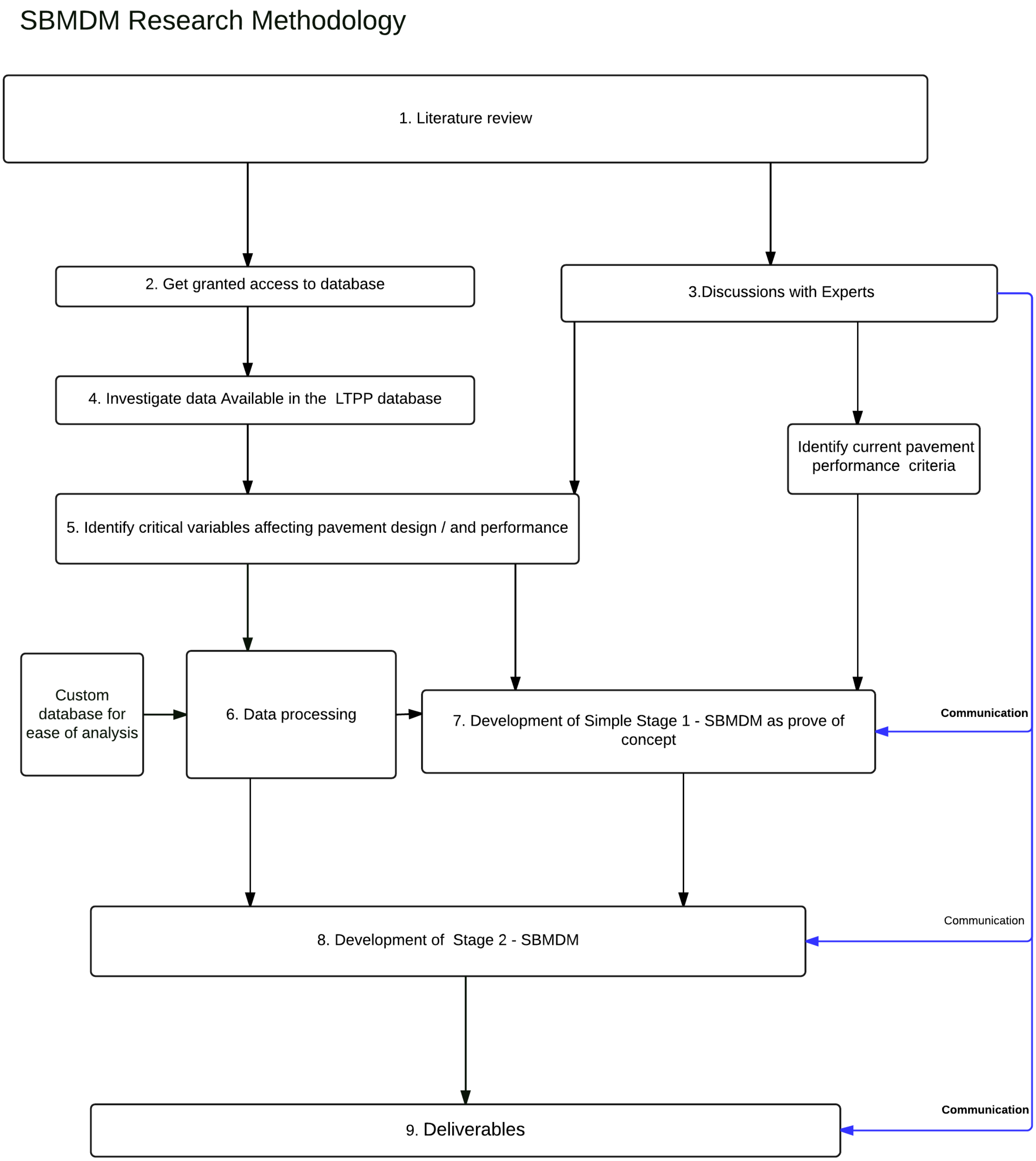



*Figure 9: Flowchart of SBMDM development method*

## 2.2. STUDY: Featurization of pavement data

This section will present the research outlining the sorting/ranking method used. This methodology's key aspect was the featurization of data which will be explained below.

### 2.2.1. Introduction

Recently a need has been identified by DOTs to extract more information out of large amounts of pavement data that has been collected over multiple years (NZTA, 2016). This need is driven by DOTs delivering value in asset management to the public. If engineers can identify pavements that are performing well, then they are better equipped to implement this knowledge to repeat pavement success. However, to identify pavements that are performing well multiple performance indicators for multiple sections must be compared over multiple years. This vast amount of data must be analysed from different dimensions to identify which pavements are performing well. It is proposed that a new tool is constructed that can deal with these problems in a logical method that informs engineers in order to repeat pavement success.

### 2.2.2. Aim and objectives

Aim: Use historical pavement performance data to identify sections of pavement that performed well to support decision making. Using Multi-Dimensional Databased, Fuzzy logic and Delphi the following objectives were answered:

- Create a data structure that is easily accessible and able to accept multiple streams of data logically.
- Develop a data structure that is pavement context focused.

- The structure must be able to accept user input to identify specific user need.
- Investigate the formation of fuzzy membership sets using data and not expert opinion.
- Make a routine to compare success.
- Demonstrate methodology using New Zealand databases as a case study.

Scope: This tool will be developed for New Zealand conditions with databases from New Zealand. However, this tool is aimed to be universal in method. It is intended that this tool could be repurposed for multiple different international databases.

To accomplish the above objectives, the literature is broken into three main parts. Firstly, identification of data structures in use in industry and research. Secondly, identify different methods of featurizing pavement performance data. Finally, review literature on the on different methods of combining featurized pavement data.

### 2.2.3. Review of data structures

Many different data management frameworks exist in computer science. The flat table has been used electronically for many years. It is the base upon which the largest data sets are held. Commonly traditional SQL (Structured Query Language) has been used in a relational database management system (RDBMS) and is the standard for the industry today. However, Golliat et al. discusses the many limitations of this standard (Colliat, 1996) and shows the benefits of moving to Multidimensional Database (MDD) approach. MDD is structured to answer quarries about trends and patterns in data. This structure is imposed so that anomalies and trends can more easily be extracted. This is commonly done with multi-dimensional analysis techniques (Larson, Lossau, & Walsh, 2011).

### 2.2.4. Review of MDD structure

The basis of MDD is the cube. Cubes are derived from fact tables. A fact table is a table containing features or measurements(Laker, 2006; Larson et al., 2011).

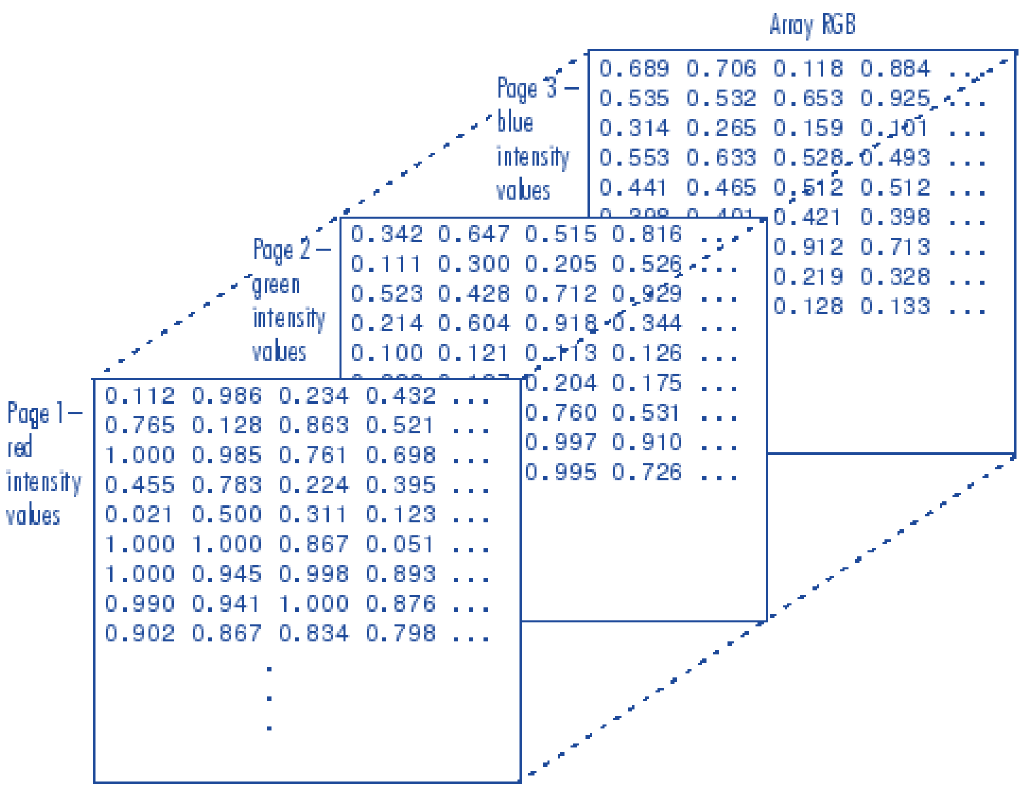



*Figure 10: Example of traditional multi-dimensional matrix used in this tool. (Adopted from Matlab, 2016)*

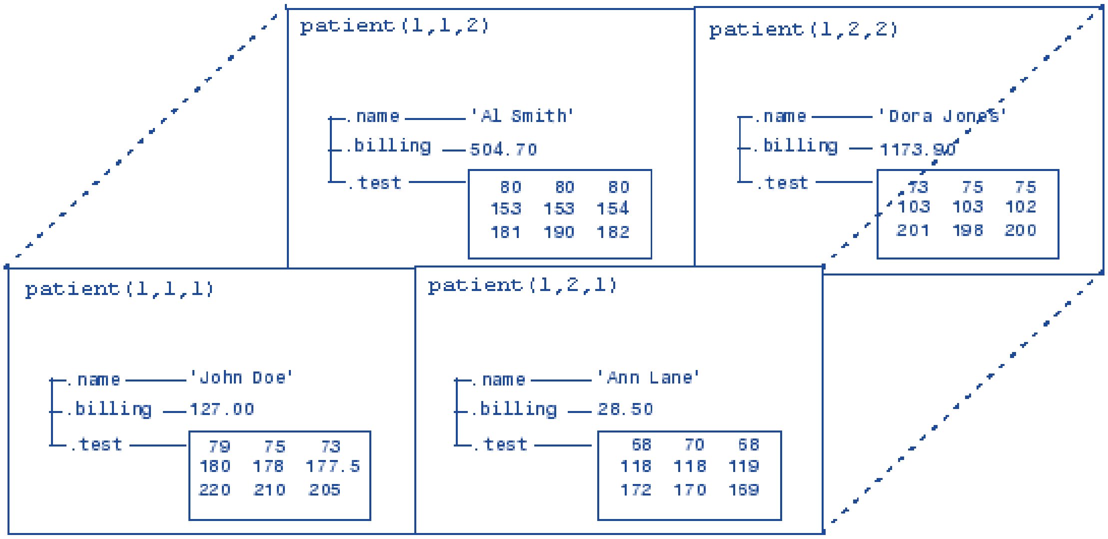



*Figure 11: Example of a multi-dimensional structure array used in this tool. This type of frameworks is more easily interpreted by engineers but is more complex to implement (Adopted from Matlab, 2016).*

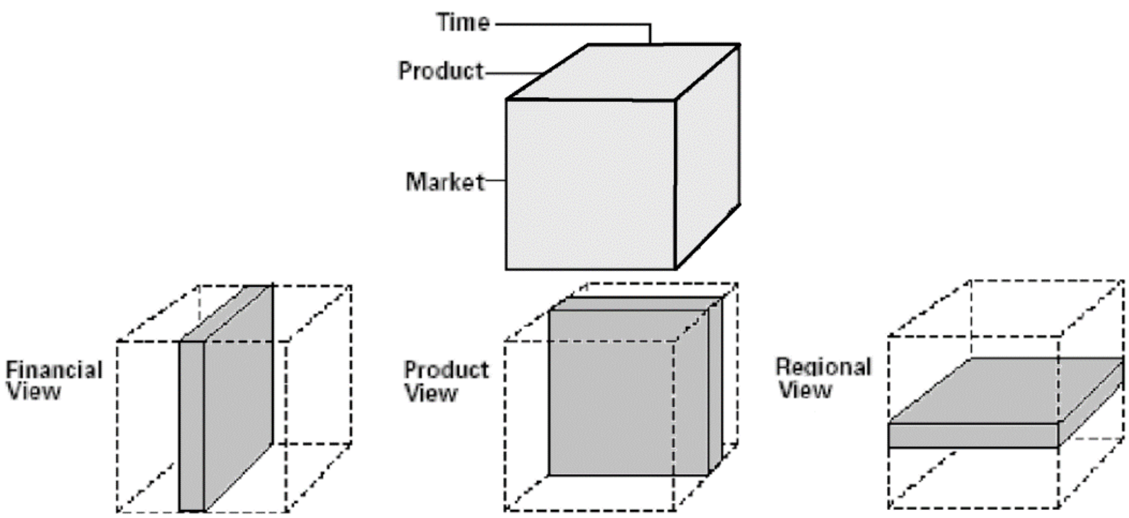



*Figure 12: Simple visualisation of multi-dimensional perspectives as it related to different entities*

Each cube has additional structures over a simple table. The cube has edges, which are also referred to as dimensions. Figure 10 shows that using the same framework; multiple parties can analyse and gather information from the same data structure.

The multidimensional framework has many advantages to the traditional database structure (Colliat, 1996; Laker, 2006; Park & Cai, 2017):

A relatively small range of authors has used the idea of multidimensional data in pavement and transportation research. Kuhn (2011) describes the limitations of using a discrete composite condition index and proposes that approximate dynamic programming can be used for large networks of pavements considering multidimensional condition data (Kuhn, 2011). Khurshid et al. (2014) used a multi-dimensional treatment methodology to evaluate five rigged pavement rehabilitation treatments. They used US LTPP data with various other data sources including climate and loading. They found that superior effectiveness of treatment does not necessarily translate to superior cost-effectiveness (Khurshid, Irfan, Ahmed, & Labi, 2014). Dock (2004) discussed the limitations of current roadway standards and suggested a multidimensional framework for context-based design of thoroughfare (Dock, Bochner, & Greenberg, 2004).

### 2.2.5. Review of featurizing of pavement data

Several methods for featurizing pavement data exists all with advantages and disadvantages. Firstly, the simplest and easiest way to featurize pavement data is to rank the pavement data on a linear scale. One of the simplest approaches normalizes the data, as shown in Equation 2.

$$Degree\ of\ performance\ (y_i) = \frac{x_i}{\max(x_{1-n})} \quad or \quad \frac{x_i}{Sum(x_{1-n})} \qquad \text{Equation 2}$$

The Second method is to featurize pavement date using a function or expression as shown in Equation 3.

$$Degree\ of\ performance\ (y_i) = Function(\ rutting(x_i), \ldots, Indocator_n(x_i)) \qquad \text{Equation 3}$$

This could take up many different forms including commonly used deterioration models, life remaining models, and engineering judgment models. This is more complex and harder to explain to practising engineers.

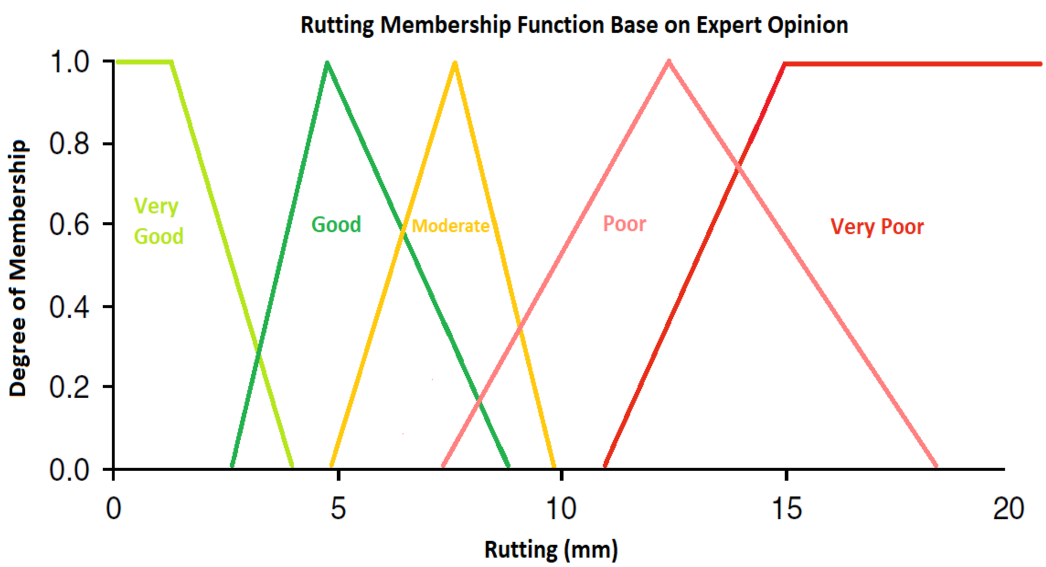



*Figure 13 Examples of a membership set based on expert opinion( adopted from (Sun & Gu, 2010))*

The third method is an arguably more complex approach called fuzzy logic. Rather than using the classical approach of saying a pavement is poor if some finite value or finite function is equal to x. Fuzzy logic instead is an approach that gives degree of truth rather than the yes and no mentality (Gunaratne, Chameau, & Altschaeffl, 1984; Gunaratne, Chameaut, & Altschaefflf, 1985; Kucukvar, Gumus, Egilmez, & Tatari, 2014; Pan, 2008; Wang, Lin, & Zhang, 2011). The key component of fuzzy logic is the formation of a fuzzy membership function. In previous research, fuzzy membership functions have been based on the variation in expert option (Sun & Gu, 2010) as shown in Figure 13.

### 2.2.6. Review of methods to combine Featurized Data

Once data has been featurized using one of the above techniques, data must still be combined to form a ranking index for identification. Sorting and ranking methods play a key part in identifying pavements that are performing well. In order to rank the performance of each segment of road, the most common and simplest approach is to combine individual performance measures into a linearly formed index (Haas, 1994; Shahin & Kohn, 1979) as shown in Equation 4. Where $w_i$ is user weights and $x_i$ is value of the pavement performance indicator (Haas, 1994).

$$Combined\ Index = \sum w_i\, x_i \qquad \text{Equation 4}$$

This method has several advantages; it is simple for engineers to communicate the method to other professionals and the public. This method establishes a unified basis for comparison of pavement performance indicators (Sun & Gu, 2010).

Another common technique for combining performance indicators is the Analytical hierarchy process(AHP)(Moazami, Behbahani, & Muniandy, 2011; Velasquez & Hester, 2013). This method is firmly based in mathematical decision theory. AHP requires a pairwise comparison of each variable (Ramadhan, Al-Abdul Wahhab, & Duffuaa, 1999; Wind & Saaty, 1980). This pairwise comparison matrix is analysed to come up with weighting matrix. Sun .L et al. (2010) used AHP and fuzzy logic theory to develop a new approach for pavement condition assessment. They demonstrated the new methodology by ranking eight road sections using fuzzy membership functions developed by experts(Sun & Gu, 2010). A common problem with AHP, however, is that as the number of variables increases, the number of pairwise comparisons increases drastically (Wind & Saaty, 1980). For this reason, many researchers have moved to the Delphi method as an alternative (Dalkey & Helmer, 1963; Linstone & Turoff, 1975; Ma, Shao, Ma, & Ye, 2011; Velasquez & Hester, 2013).

The Delphi method is a communication technique where a panel of experts answers questions in two or more rounds. After each round, anonymous feedback for choices and reasoning. The panel is then asked to re-evaluate their choices in the next round (Dalkey & Helmer, 1963; Linstone & Turoff, 1975; Ma et al., 2011). The key principle of the Delphi method is that decisions made by a structured group are more accurate than those made by an unstructured group (Rowe & Wright, 2001).

### 2.2.7. Tool's Development

This tool has been written in various programming languages and built from the ground up, instead of explaining the implementation detail of the tool, this chapter will instead focus on the information structure that determined the overall function of the tool.

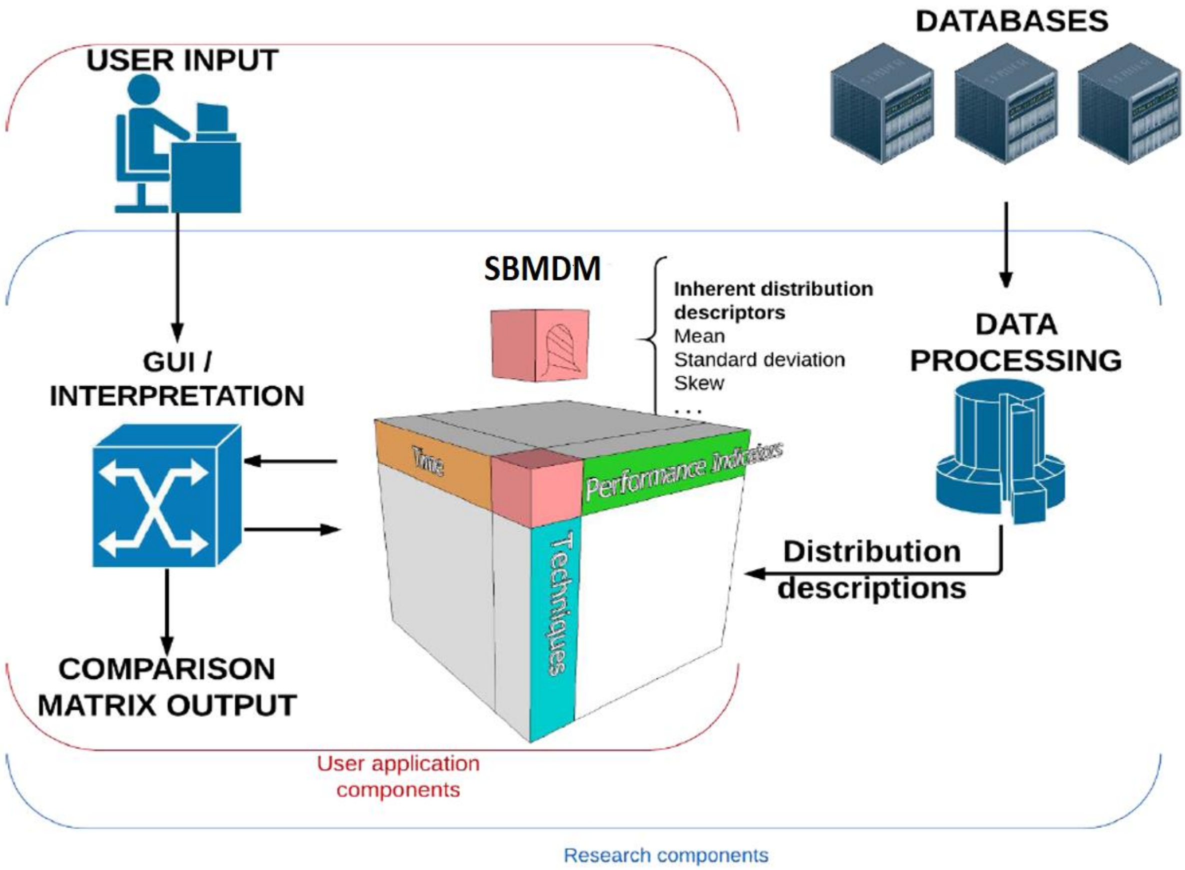



*Figure 14: Information structure of the SBMDM*

### 2.2.8. Development of the matrix structure

Development of the tool was conducted in Matlab, and Python (both dynamically typed programming languages) as these languages had obvious advantages within build matrix computation functionality and extensive libraries. The first step was to implement the matrix framework. Both frameworks were used as shown in Figures 10-11. Numerical analysis is conducted in the traditional MDM; this would be then converted to the MDM structured array shown in Figure 11. This allowed for both a functional and context focused (more easily understood by engineers) implementation.

It was chosen that the three key dimensions of the matrix cube would be pavement sections, performance indicators and time as shown in Figure 14.  This framework would allow for extensive expandability in any dimension. This meant that variables and functionality could be added and subtracted to the matrix at any time. Once the data structure was implemented, data sources had to be chosen. The tool was constructed in such a way that data could come from a range of different sources. This meant that the tool could interface with data structures using a variety of different languages and APIs.

### 2.2.9. Development of data processing component

Data sources would be processed using the data processing module shown in Figure 14. This component is made up a range of key functions. Firstly, it would allow multiple different database types and configurations to be accessed by the tool and imported for analyses at the access level. Secondly, this tool would analyse the dataset and assess different distribution descriptors like mean, max, min, mode, median, skew and quality of fit. These fundamental distribution descriptors were chosen so that any engineer would instantly be able to understand the processed data. This functionality could be expanded to include many more advanced methods.  Finally, it would assign locations within the Stochastic Based Multi-Dimensional Matrix and push data to be stored in the framework.

### 2.2.10. Development of interpreter component

Interpretation component is in place to take user inputs, evaluate them against the SBMDM and then produce a comparison matrix output that the user can then use. The Interpreter has many functions. Firstly, effectively allow engineers/professionals to select outputs they are interested in. This requires two key processes:

*1- Featurization of pavement data*
*2- Combining featurized Data*

Process 1– Featurization of pavement

From the literature review, three key methods to features pavement data have been established. By comparing the advantages and disadvantages (shown in table 4) of these methods researchers established that fuzzy logic approach was the most appropriate for their needs.

*Table 4: Showing the advantages and disadvantages of three different featurization techniques*

| *Featurization Technique* | *Advantages* | *Disadvantages* |
|---|---|---|
| *Linear Formed* | Simple to understand and explain to practitioners | - Not data driven.<br>- Overly simplified model |
| *Function-Based* | - Moderately complex system<br>- Uses existing research knowledge to quantify deterioration<br>- Generally based on correlation and regression analysis | - Does not account for variability Deterioration functions have not yet been developed for all pavement performance indicators<br>- Sometimes requires many input variables that are not available.<br>- Does traditionally account for variation in ranking |
| *Fuzzy Logic* | - In-depth Analysis.<br>- Can be used for specific analyses but also a holistic point of view.<br>- Can be heavily data driven as well as use expert opinion.<br>- Membership functions can be developed for performance indicators that do not have a function modelled approach. | - Complex system hard to explain to practitioners<br>- Statisticians have reservation about the technique as the model loses statistical meaning<br>- Can be hard to interpret results |

A key component of fuzzy logic is the identification of fuzzy membership sets. Unlike previous research, membership functions were chosen based on performance data and not expert option. The membership functions were formed through the following steps:

*Table 5: Showing Percentile relation to qualitative property*

| *Percentile Value(P)* | *1%(0.01* | *25%(0.25)* | *50%(0.5)* | *75%(0.75)* | *99%(0.99)* |
|---|---|---|---|---|---|
| *Quality* | Very Good | Good | Moderate | Poor | Very Poor |

Firstly, distribution descriptors are pulled from the SBMDM, for example, $logMu_1$ and $logSigma_1$. Secondly, the corresponding values for percentiles shown in Table 5 are extracted from the distribution as shown in Equation 5.

$$[VeryGood_{array\ 1-n}] = f(P, [LogMu_{1-n}], [LogSigma_{1-n}]) \qquad \text{Equation 5}$$

Where:

P = 0.01 (Very Good)

*f* = Percentile Function(MathWorksInc, 2017)

Thirdly, this process is then repeated until all data within the given context is analysed and a sufficiently large “Very good” array has been constructed. This array is then fitted (see figure 16 in the case study) and normalised between 0 – 1 to form the very good component for the membership function.

Finally, this process is then repeated so that all percentiles in Table 5 form the complete membership function for one performance indicator. A similar process is then followed to construct membership functions for other performance indicators. An example of these membership functions can be seen in the case study, Figures 17-19. It is important to note some performance indicators, ‘perform better’ in ascending order where others are ‘perform better’ in descending order.

Once membership functions have been formed the Rational set (R), and Normalized Rational set (NR) can be formed. These are constructed from reading the membership functions. For example, this is where a single rut value is broken into degrees of truth and expressed as five distanced indexes. This is distinctly different from a traditional approach where a pavement section would be allocated a single index. For a further detailed explanation of fuzzy logic, please see research done by (Sun & Gu, 2010).

$$R = [VGoodDoM, GoodDoM, ModerateDoM, PoorDoM, VPoorDoM]$$ Equation 6

$$NR = [\frac{VGoodDoM}{Sum(R)}, \frac{GoodDoM}{Sum(R)}, \frac{ModerateDoM}{Sum(R)}, \frac{PoorDoM}{Sum(R)}, \frac{VPoorDoM}{Sum(R)}]$$ Equation 7

Process 2 - Combining Featured data

*Table 6: Comparison of different techniques used to combine featurized pavement data*

| *Combination Technique* | *Advantages* | *Disadvantages* |
|---|---|---|
| *Combined index* | - Simple to understand and explain to practitioners.<br>- Extremely fast to implement | - Not data driven.<br>- Can be overly simplified<br>- Is often based on single person's opinion |
| *Delphi* | - Expert prefers this method when comparing large amounts of indicators.<br>- Experts are more forthcoming as this method encourages discussion.<br>- Moderately complex system<br>- | - Is not based on decision theory<br>- Require multiple experts<br>- The slow process of going through each round until expert agree or the technique concludes. |
| *AHP* | - In-depth Analysis.<br>- Can be used for specific analyses but also a holistic point of view. Can be heavily data driven as well as use expert opinion. | - Complex system hard to explain to practitioners<br>- Can be extremely slow<br>- Consistency between expert can be a major issue<br>- Pairwise comparisons take time.<br>- Generally expert are not forthcoming when making pairwise comparisons |

From the literature review, three candidate methods of combining featurized performance data were identified. Regardless of the method chosen, all discussed methods strive to find some form of a normalising weighting vector that indicates the importance of different performance indicators. From previous experience, it has found that experts in the pavement field tend to have low participation when given pairwise comparisons. Experts favour a more discussion based technique. By comparing the advantages and disadvantages of all these methods researchers established that Delphi approach was the most appropriate. The exact values in the weighting vector W are context specific, but the vector will take the form shown in Equation 8.

$$W = [Rutting(W_1), \quad IRI(W_2), \quad PerformanceIndicator_n(W_n)] \qquad \text{Equation 8}$$

### 2.2.11. Combining Fuzzy Relational sets

The combination of the weighting set W with fuzzy normalised Relational Sets happens as shown in Equation 9.

$$EvaluationSet = W \otimes NR \qquad \text{Equation 9}$$

If we analysed the Evaluation Set from Equation 9 and found the largest index value, this can then use to classify all sections into one of 5 groups, VeryGood - VeryPoor. This is a simplistic method of ranking the sections, called the Winner Takes All (WTA) approach.

$$DWCI = \ Evaluation\ Set * \begin{bmatrix} 0.333 \\ 0.267 \\ 0.200 \\ 0.133 \\ 0.067 \end{bmatrix} \qquad \text{Equation 10}$$

When combing this ranking method above with the SBMDM, it becomes a powerful tool that let you analyses pavement data in multiple dimensions. This will be further demonstrated in the following case study.

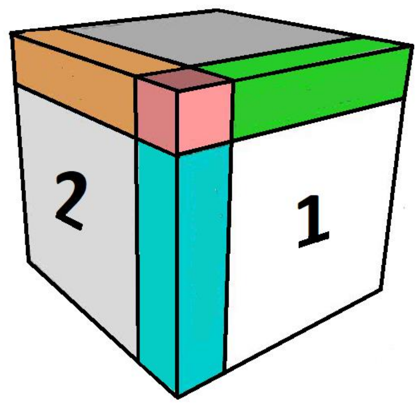



*Figure 15: Abstracted diagram of the matrix*

### 2.2.12. Case study

In recent years, many LTPP programs have come of age, and recently a need has been identified to better understand LTPP data. While the original purpose of the LTPP studies was to better calibrate deterioration models, there is much to learn when comparing data between LTPP sections.

The LTPP database was used to establish a range of sections of pavement to be compared. The LTPP could give us performance indicators such as rutting, roughness and texture measurements and store all LTPP data from the year of its inception in 2001. These measurements have been recorded in both the left and right wheel path over multiple years with specialised equipment.

For this case study, the objective was to rank pavement sections from a holistic New Zealand context. This meant that all pavement data was used in the construction of the membership functions.

### 2.2.13. Case study scope

- Only the three main performance indicators in the NZ LTPP will be considered. These are Rutting(mm), Roughness (IRI) and Texture(MPD).
- All sterile LTPP sections will be used to form the membership functions.
- For simplification, the number of section to be ranked have been decreased to 10 (see Table 7)

Using the membership function construction technique outlined in the methodology the following membership functions where established shown in Figure17-19. The Delphi method was employed on pavement experts in New Zealand. The experts were from the New Zealand National Pavements Technical Group who make up leading pavement experts in New Zealand. Using the Delphi method with this group the following normalised weighting vector was established.

$$W = \begin{matrix} Rutting(W_1) & IRI((W_1) & Texture(W_1) \\ 0.45 & 0.35 & 0.2 \end{matrix} = [0.45\ ,0.35,0.2] \qquad \text{Equation 11}$$

Equation 11 shows that rutting and IRI is a preferred performance indicator over texture. It also shows that rutting is more preferred than IRI. The expert reasoning behind this is that because New Zealand’s most common pavement technology is chip sealing over a gradual base, rutting is more important than would be the case in other countries Like the US where AC is the more common technology. This vector is only applicable to New Zealand condition and the context of New Zealand.

## 1.1 Case study results

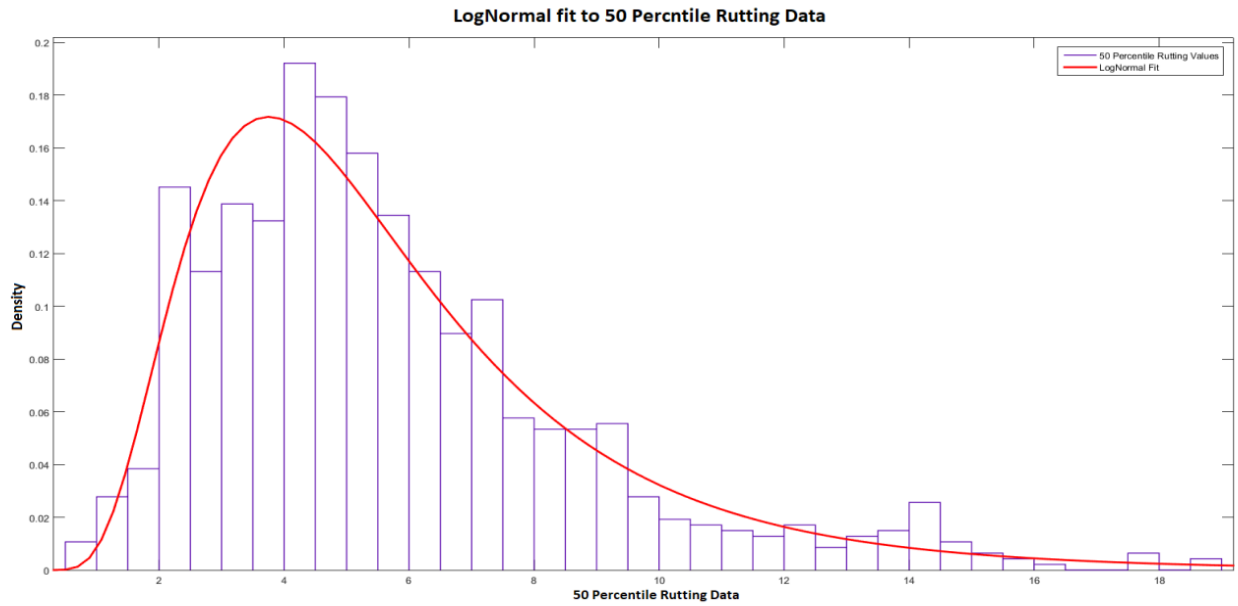



*Figure 16: Lognormal probability density function for 50 percentile rutting values for all sterile NZ LTPP sections (Mu=1.61, Sigma = 0.53, mean = 5.8)*

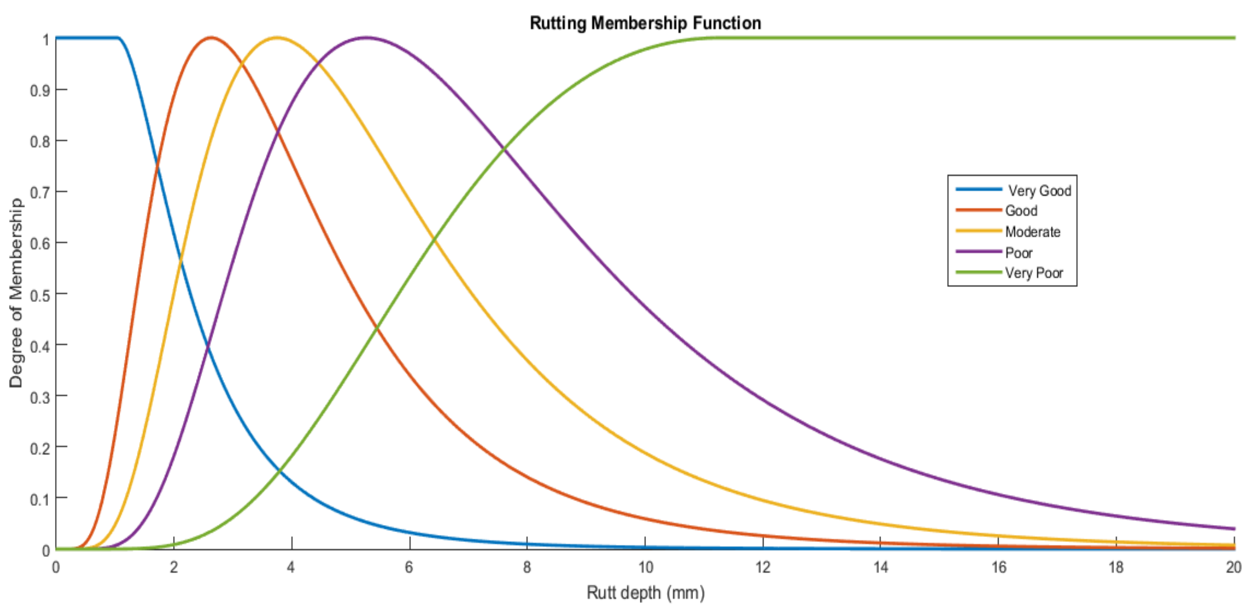



*Figure 17: Rutting membership function*

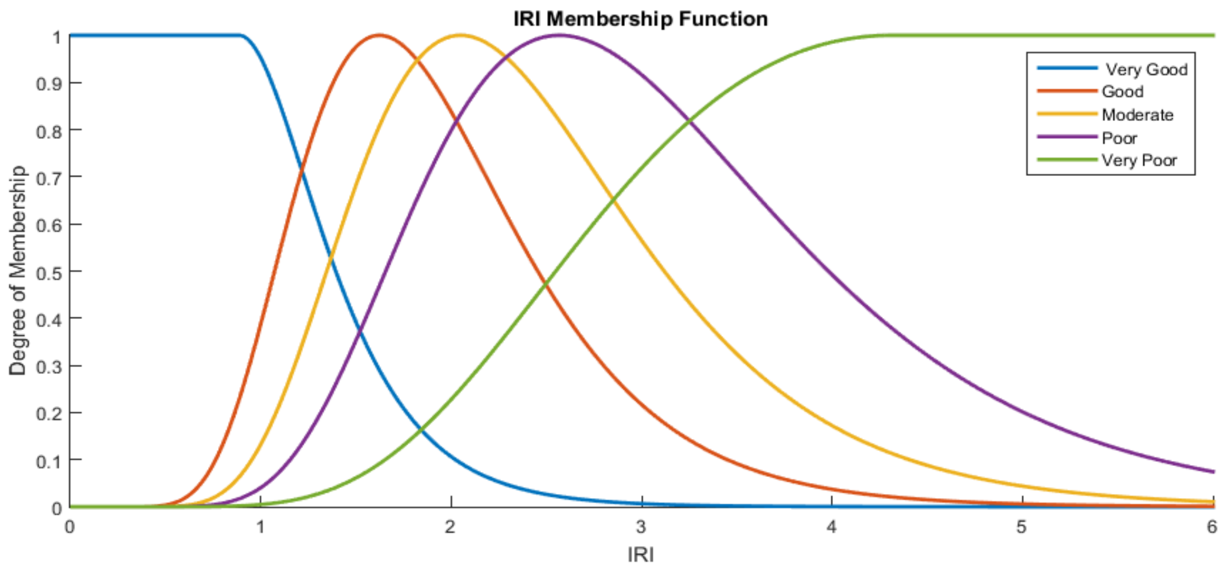



*Figure 18: IRI membership function*

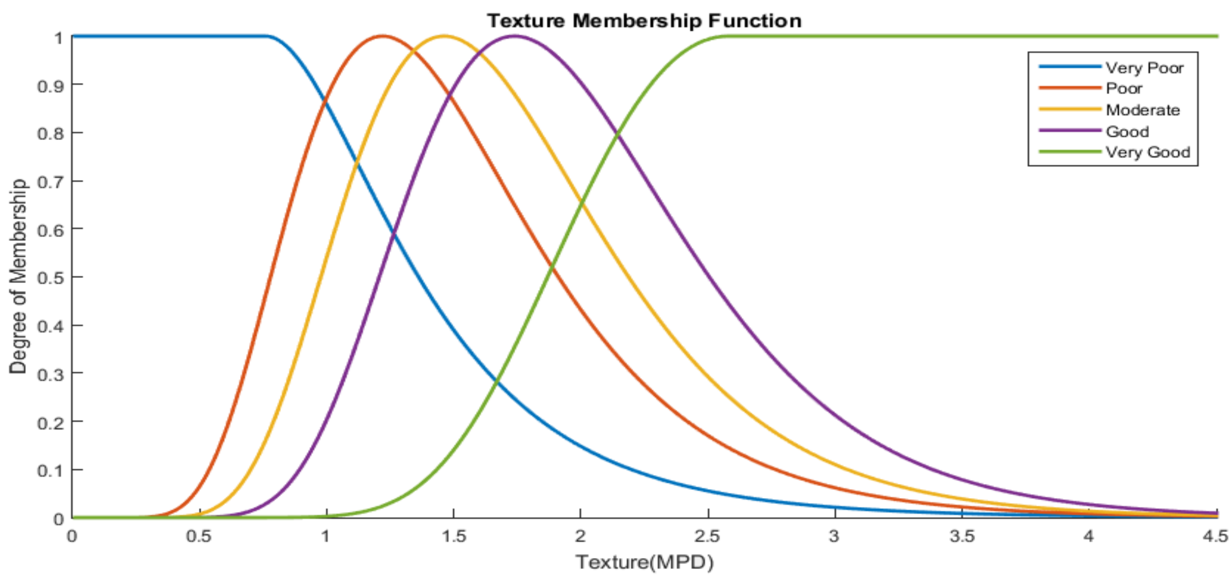



*Figure 19: Texture membership function*

*Table 7: Showing 10 LTPP sections that have been ranked in the first dimension*

| *Section* | *DWCI* | *WTA* | *Very Good* | *Good* | *Moderate* | *Poor* | *Very Poor* | *Rutting* | *IRI* | *Texture* |
|---|---|---|---|---|---|---|---|---|---|---|
| *'CS_7a'* | 0.223 | 1 | (0.364 | 0.261 | 0.127 | 0.044 | 0.003) | 1.985 | 0.960 | - |
| *'CS_26'* | 0.200 | 3 | (0.065 | 0.287 | 0.312 | 0.261 | 0.076) | 4.505 | 1.592 | 1.500 |
| *'CS_33'* | 0.191 | 4 | (0.136 | 0.172 | 0.253 | 0.296 | 0.143) | 6.064 | 2.279 | 2.794 |
| *'CS_20'* | 0.179 | 4 | (0.029 | 0.207 | 0.307 | 0.327 | 0.129) | 4.954 | 2.446 | 1.628 |
| *'CS_24'* | 0.167 | 4 | (0.043 | 0.182 | 0.248 | 0.297 | 0.230) | 8.057 | 2.138 | 1.864 |
| *'CS_11'* | 0.156 | 5 | (0.077 | 0.133 | 0.187 | 0.256 | 0.347) | 10.810 | 2.454 | 2.237 |
| *'CS_14'* | 0.154 | 5 | (0.081 | 0.108 | 0.180 | 0.307 | 0.323) | 7.801 | 3.399 | 2.298 |
| *'CS_29'* | 0.151 | 4 | (0.011 | 0.129 | 0.244 | 0.345 | 0.271) | 5.201 | 3.637 | 1.259 |
| *'CS_60'* | 0.141 | 5 | (0.012 | 0.108 | 0.206 | 0.332 | 0.342) | 8.584 | 3.114 | 1.519 |
| *'CS_22'* | 0.124 | 5 | (0.005 | 0.091 | 0.169 | 0.228 | 0.506) | 16.022 | 2.329 | 1.027 |

Table 7 shows the ten LTPP pavement sections that have been ranked to DWCI. In this case study of 10 sections, CS_7a is performing the best whereas section CS_22 is performing the worst. From this table, we can also see the WTA index number which corresponds well with the DWCI. It is interesting to note that although section CS_7a did not have a Texture reading it was still ranked first in DWCI. This is because there was very little weight put on texture measurements by the expert group but it performed extremely well in the other two performance indicators. Not having texture data would give section CS_7a an advantage with regards to WTA, however, would be a disadvantage to the DWCI score.

Up until this point, this case study has focused on the frontend 2D slice as shown in Figure 15 as ‘1’. This 2D slice has edge variables of ‘Pavement sections’ and ‘Performance Indicators.’ Next, the 2D slice denoted as ‘2’ in Figure 13 will be queried. This two-dimensional data slice has the edge variables as ‘Pavement Sections’ and ‘Time.’ In this case, ‘Time’ is measured in years. If all years was treated equal, therefore, W (i – end) = 1. It is possible to use the tool to rank the sections across all years of data. The results of this request to the tool presented in Table 8.

*Table 8: Showing 10 LTPP sections that have been ranked to DWCI in the second dimension, Rutting*

| *Section* | *DWCI* | *WTA* | *Very Good* | *Good* | *Moderate* | *Poor* | *Very Poor* |
|---|---|---|---|---|---|---|---|
| *CS_7a'* | 0.102 | 2 | 0.121 | 0.124 | 0.101 | 0.061 | 0.007 |
| *'CS_26'* | 0.073 | 4 | 0.008 | 0.069 | 0.124 | 0.162 | 0.085 |
| *'CS_29'* | 0.071 | 4 | 0.006 | 0.062 | 0.120 | 0.167 | 0.093 |
| *'CS_33'* | 0.071 | 4 | 0.006 | 0.061 | 0.118 | 0.165 | 0.098 |
| *'CS_20'* | 0.063 | 4 | 0.004 | 0.045 | 0.097 | 0.158 | 0.144 |
| *'CS_24'* | 0.062 | 5 | 0.005 | 0.044 | 0.088 | 0.145 | 0.166 |
| *'CS_14'* | 0.061 | 4 | 0.003 | 0.040 | 0.091 | 0.157 | 0.157 |
| *'CS_11'* | 0.049 | 5 | 0.002 | 0.020 | 0.052 | 0.112 | 0.262 |
| *'CS_22'* | 0.038 | 5 | 0.000 | 0.005 | 0.019 | 0.063 | 0.361 |
| *'CS_60'* | 0.035 | 5 | 0.001 | 0.018 | 0.047 | 0.094 | 0.116 |

The order of section in Table 9 has not changed significantly, and this was to be expected. The reason for this is that rutting governed the selection in the results from Table 8.

*Table 9 Table ranking sections to overall DWCI across all three indicators*

| | *OVERALL_DWCI* | RUT_DWCI | RUT_WTA | IRI_DWCI | IRI_WTA | TEX_DWCI | TEX_WTA |
|---|---|---|---|---|---|---|---|
| CS_7A' | *0.117* | 0.102 | 2 | *0.202* | *1* | 0.000 | NAN |
| 'CS_33' | *0.116* | 0.071 | 4 | *0.130* | *3* | 0.190 | 1 |
| 'CS_26' | *0.109* | 0.073 | 4 | *0.153* | *2* | 0.114 | 4 |
| 'CS_24' | *0.105* | 0.062 | 5 | *0.134* | *3* | 0.151 | 2 |
| 'CS_20' | *0.097* | 0.063 | 4 | *0.124* | *4* | 0.128 | 3 |
| 'CS_14' | *0.089* | 0.061 | 4 | *0.092* | *5* | 0.149 | 2 |
| 'CS_11' | *0.088* | 0.049 | 5 | *0.115* | *4* | 0.129 | 3 |
| 'CS_22' | *0.085* | 0.038 | 5 | *0.127* | *4* | 0.115 | 4 |
| 'CS_29' | *0.080* | 0.071 | 4 | *0.083* | *5* | 0.095 | 4 |
| 'CS_60' | *0.055* | 0.035 | 5 | *0.062* | *4* | 0.086 | 3 |

### 2.2.14. Discussion

It is of paramount importance to the credibility of the output ranking that researchers and users recognize that both the featurization step and combination set is extremely context specific. In the case study above a holistic point of view was taken that included all sterile LTPP sections. This meant that the position and variability included in the membership in Figure 17-19 sections are representative of the whole New Zealand Pavement network assuming a representative sample was taken from the network when the LTPP program was established which previous research suggests is the case. When determining the combination vector (W) through the use of the Delphi method it was made clear to the experts in question the ratings were for the context of the whole of New Zealand.

Membership functions can only be constructed if enough raw data is available to fit a statistical distribution. In the above case study, a wide context was set. However, as you refine the membership context the amount of data could reduce to a point where distributions can no longer be reliably fitted. At this point, the membership functions lose significance and rankings are no longer reliable.

It is important to note that once the distributions were normalized to form the membership functions, it lost all statistical meaning. If we were to read a value of 0.5 of one of the membership functions, this would have no meaning statically to the probability of 0.5. The area under the curve does not sum to 1 as it should for a probability distribution. Instead, the normalised distribution is conveying the degree a value matches with the distribution.

Recommendations

- Expand on the number of performance indicators from different databases.
- Investigate a method to feature weighting vector W from data, not expert opinion
- Formations of different membership functions considered different contexts. An example could induce the comparison of roads in different regions.

### 2.2.15. Conclusion

A need has been identified by DOTs that urge researchers to develop tools to extract more information out of ageing pavement databases. A new tool has been demonstrated to help understand pavement condition data from a holistic point of view. This tool incorporates Multi-dimensional databases, Fuzzy logic, and the Delphi method. Fuzzy Membership sets are established through performance data and not expert opinion. This tool can rank pavement sections based on a range of factors that are the most appropriate to the user. This tool informs engineers which pavement is performing well to repeat pavement success. This chapter has demonstrated the tool through the use of a case study where three performance indicators were analysed from the New Zealand LTPP.

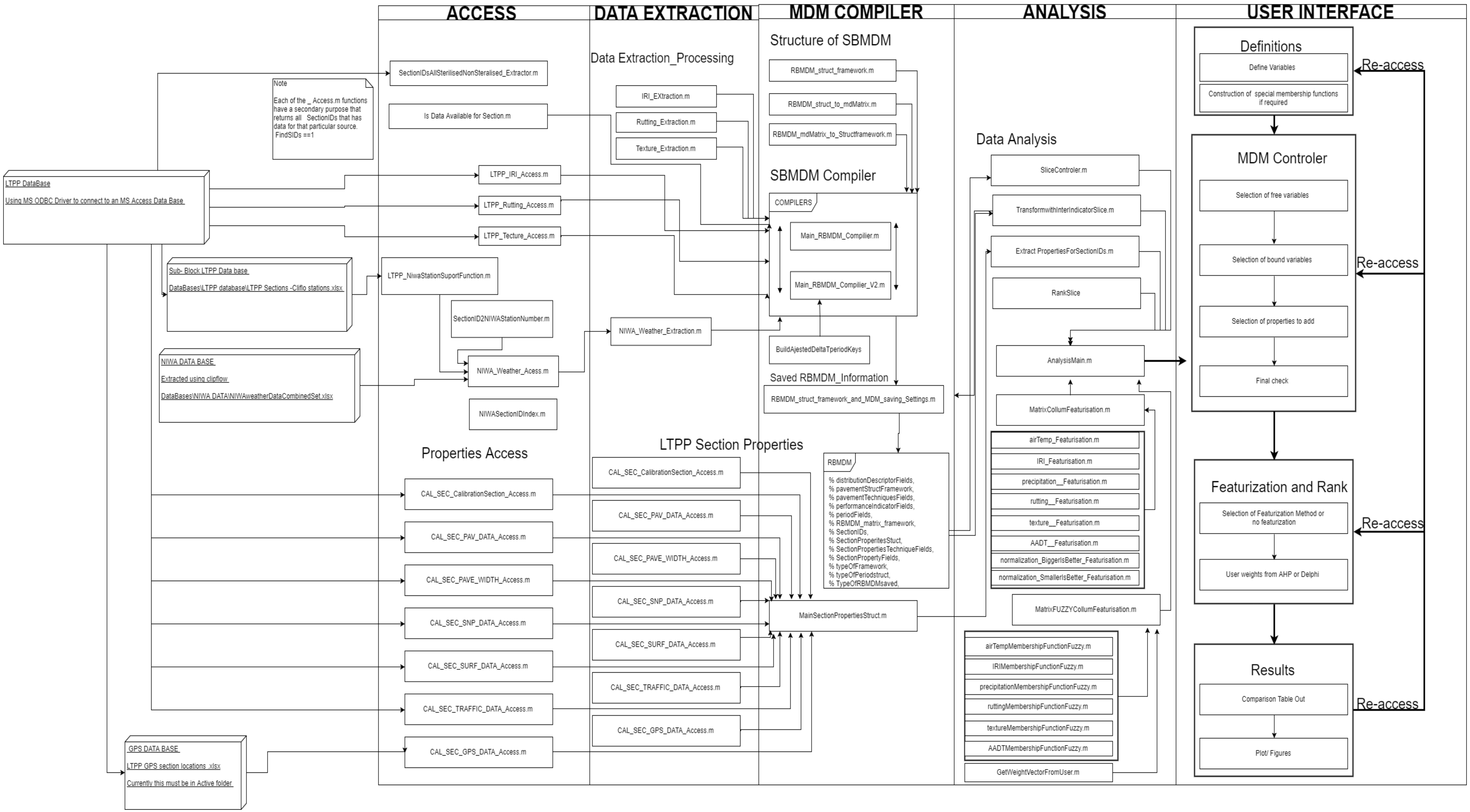



*Figure 20: Functional flow diagram of key components in the SBMDM*

## 2.3. Functional structure

The SBMDM is broken up into five key levels called; Access, Data Extraction, MDM Compiler, Analysis and User Interface as can be seen in Figure 20. Each Leave has a specific overall function in the larger context of the SBMDM tool. These levels will be discussed in the following sections. It is important to note that the functions presented in Figure 20 are high level and at the top of the function hierarchy. These functions require many more supporting functions to operate.

### 2.3.1. Data access level

The key function of the Access level is to allow the SBMDM to communicate with other databases and data sets. This level has the following key goals:

- Allow the tool to communicate with a large range of databases and data sets.
- Must be versatile to communicate with different database frameworks and file types effectively.
- Must allow for expandability.
- Allow SQL quarries to be initiated from inside the tools native language.

This tool can connect to standard ODBC (Open Database Connectivity)-compliant and JDBC(Java Database Connectivity ) -compliant databases, including Oracle®, SAS®, MySQL®, Sybase®, Microsoft® SQL Server®, Microsoft® Access™, and PostgreSQL®. This tool can also connect to more common data files like CSV, TSB, XLS, and SLSX (Microsoft Excel®).

```
performanceIndicatorFields =

    'LWPrutting'
    'RWPrutting'
    'LWPDecreasingRutting'
    'RWPDecreasingRutting'
    'LWPIncreasingutting'
    'RWPIncreasingrutting'
    'LWPIRI'
    'RWPIRI'
    'LWPDecreasingIRI'
    'RWPDecreasingIRI'
    'LWPIncreasingIRI'
    'RWPIncreasingIRI'
    'LWPtexture'
    'RWPtexture'
    'LWPDecreasingTxt'
    'RWPDecreasingTxt'
    'LWPIncreasingTxt'
    'RWPIncreasingTxt'
    'rainfall'
    'temprature'
```

*Figure 21 Current performance indicators in the matrix*

This level is also responsible for accessing pavement section properties. These properties are pulled from databases that include, LTPP and NIWA (Figure 22). As has been previously discussed, RAMM is the most unreliable database. Therefore, RAMM data was only used to investigate the general context.

```
sterilised:
regionMantenance:
AADT:
PersentageHeavy:
SurfDate:
SurfDateLTPPStartDiffrence:
SurfMatRAMM:
SurfMatTestPit:
chipSize:
chipSizeRamm:
surfaceDepth:
baseDate:
baseMaterial:
baseThickness:
SubBaseMaterial:
SubBaseThickness:
backAnalysedSNPAverage:
width:
NoOFLanes:
GPSLong:
GPSLati:
GPSStartElevation:
GPSEndElevation:
GPSchangeinElevation:
GPSLongDecreasing:
GPSLatiDecreasing:
GPSLongIncreasing:
GPSLatiIncreasing:
```

*Figure 22: Section properties currently included in the SBMDM*

### 2.3.2. Data extraction level

The key component of the data extraction level is to process incoming data. This involves computing multiple distribution descriptors as shown in Figure 23. Before this can occur the tool must check the data for common errors. For example, these checking functions evaluate that rutting and rainfall are not less than 0.

The extractor level has the following goals:

- Sorting information
- Error checking
- Fitting distributions
- Data analysis for quality of fit.

```
distributionDescriptorFields =

    'mean'
    'stdv'
    'skew'
    'qualityOfFit'
    'max'
    'min'
    'mode'
    'median'
    'logMu'
    'logSigma'
```

*Figure 23: Distribution descriptors currently included in the SBMDM*

### 2.3.3. MDM compiler level

Once the distribution descriptors have been extracted for the various performance indicators for the various years, this data must then be added to the MDM.

At this level is where the Section Properties stuct is also constructed to hold information displayed in Figure 22 for all pavement sections.

The MDM Compiler level has the following goals:

- Setup the traditional – Multidimensional framework (best interpreted by computer, setup for computational speed)
- Set up the Object-Orientated (OO) Multidimensional framework (Context focused easier for engineers to understand, slower)
- Construct the OO Section properties framework

- Enter values from the previous level into the tree structures mentioned above and check/ Assert.
- Allow for different matrix indexing (shown V1 and V2 in Figure 20)
- Save the completed structures effectively to disk for analysis at any time, therefore no need to 'Compile' at runtime.

### 2.3.4. Analysis level

The Analysis level is designed so that with the aid of the User Interface level the complied structures can be effectively accessed and examined by the user. This involves implementing the ranking methodologies previously discussed in this chapter.

The Analysis Level has the following goals:

- Control the different dimensions of the SMDM and ensure that the correct variables are assigned for analysis.
- Allow for external data to be compared.
- Allow for the ability to featurise and rank pavement data using methods previously discussed.
- Allow for the visualisation of data quickly though uses of plots and tables. (Future work 3D plots and VR interface)

### 2.3.5. User interface level

The GUI /Interpretation Level will take user inputs, evaluate them against the SBMDM and then produce a comparison matrix output that the user can then use. Figure 14 shows red brackets that show the components that are necessary to form a user application in the future. Note that these components are relatively lightweight and avoid connecting to the original databases which are extremely large. Lastly, Figure 14 shows the blue brackets; this includes the components which will be developed during this research. The current user interface is text-based similar to any command prompt interface.

The User interface level has the following goals:

- Allow for effective control of the data analysis level
- Make it relatively easy to enter and define variables from the user.
- Allow the user to add data streams.
- Allow the user to visualise data using tables and plots.

## 2.4. Chapter 2 conclusions

This chapter reviewed the key components of the research methodology with a focus on the key research points instead of the implementation detail. This chapter reviewed the key research milestones. Following this chapter 2 presented a research study outlining the sorting methodologies used. Finally, the chapter outlined the functional implementation of the developed tool.

# Chapter 3 Quality of data

# Purpose of this chapter

Before the research could proceed, discussion with experts identified an issue with regards to how the LTPP data was collected. This chapter will present a study that investigates the issue and shows how the results became relevant for contractors to help improve chip seal deterioration.

## 3.1. Introduction Chapter 3

Most of New Zealand's rural state highways can be considered low volume roads. The typical pavement consists of a sprayed chip seal layer over an unbound granular base. Anecdotally, pavement design assumptions dictate that these pavements be constructed in uniform layers as it is assumed that the wheel paths are relatively wide.

Pavement condition data, such as rutting, roughness, texture and falling weight deflectometer (FWD) measurements are used to make maintenance decisions. The condition measurements must be taken in the correct locations concerning the wheel paths to be meaningful as the pavement surface condition depends significantly on the lateral position of traffic.

Data for the Long-Term Pavement Performance program (LTPP) in New Zealand, has been collected since 2001 (T.F.P. Henning, 2008). The investigation of previous research shows that data from the LTPP was collected to a research standard. The data was collected by professionals with industry standard or international standard or better equipment for New Zealand conditions. Data were entered by professionals fluent in the pavement field. For the full methodology of the data collection process, please see the work done by (Brown, 2005).

The position of data measurement for the LTPP had been fixed before the actual wheel paths were established, see Figure 24. Finding the wheel paths can be particularly difficult in some situations (Brown, 2005). A visual estimation methodology has been adopted to find the lateral position of wheel paths. As noted by Henning et al. for modelling purposes the location of the data collection cannot be changed once established. This would introduce an extra variable into deterioration modelling (TFP Henning, Costello, Dunn, Parkman, & Hart, 2004). However, it is important to this research that the data is indeed collected in the right location.

Chip seal pavements require periodic maintenance including resurfacing. Resurfacing of chip seal pavements is done by spraying a layer of bitumen followed by spreading chips over the existing pavement. The most commonly used resealing strategy includes applying a constant rate of bitumen across the entire width of the road. This process could, therefore, apply too much bitumen in the wheel paths, causing flushing, and not enough in the other areas, causing ravelling (Douglas Gransberg & Pidwerbesky, 2007).

*Figure 24: Typical LTPP calibration section showing marked wheel paths*

*Figure 25: TIRTL experimental setup*

*Figure 26: Flushing in the wheel paths on a chip seal pavement in Rural Canterbury New Zealand.*

Flushing is caused by a combination of high pavement temperatures and heavy vehicle loading, and therefore is usually observed within the wheel paths as shown in Figure 26 (D Gransberg, Pidwerbesky, & James, 2005). Ravelling is the loss of chips, usually from parts of the road where the traffic loads are occasionally applied. After a resealing procedure, chips on the surface of the road develop a better bond with the underlying bitumen layer as vehicle loads are applied to them. This bond is weaker in the regions of the pavement where vehicle loads are not frequently applied and further weakens with the ageing of bitumen. The weaker bond between the chips and the bitumen layer could cause the chips to be swept off the pavement. Both flushing and ravelling adversely affect the skid resistance of pavements, causing safety concerns (La Bar, Rizzutto, Johannes, & Bahia, 2015).

These issues are now able to be addressed by a technology known as the variable transverse application of bitumen, where the application rate of bitumen is varied across the width of the road. This allows bitumen to be used more effectively by using a lower application rate for the wheel paths and a high application rate for the shoulder and centreline areas. The lower application rate of bitumen over the wheel tracks would ensure that the chips do not sink into the bitumen layer. Whereas the higher application rate over the areas in proximity to centreline and the edge line would ensure a better bond between the chips and the bitumen layer during the initial rolling (Bryan Pidwerbesky & Waters, 2007).

The major problem with the use of this technology is that there is no well-established design method to determine the regions where the rate of applied bitumen needs to be high or low (La Bar et al., 2015). At present this is done by visually identifying the wheel paths where flushing has occurred, but ideally, pavement resealing needs to be done before visual signs of deterioration appear (D. D. Gransberg & James, 2005). Visual inspections do not always identify the correct failure mechanism. For example, distinguish longitudinal cracking from fatigue cracking. At present, the determination of wheel paths is an approximation dependant on the experience of relevant technical staff.

The objective of this chapter is to present a methodology to estimate the lateral wheel path distribution in New Zealand.

Use this methodology to:

- Investigate the lateral position of LTPP data-collection by comparing the actual lateral distribution of vehicles using the Infra-Red Traffic Logger (TIRTL) with the LTPP measurement points.

- Investigate lateral position of wheel paths on two-lane straight roads to provide data on vehicle positioning to help contractors better calibrate the variable bitumen spray bar.
- Investigate anecdotal pavement design assumption regarding wheel path width.
- Complete a preliminary investigation on lateral distribution of vehicles on a curved road section and investigate potential issues.

## 3.2. Chapter literature review

A range of studies has investigated the lateral position of vehicles on asphalt and concrete highways internationally (Buiter, Cortenraad, Van Eck, & Van Rij, 1989; Islam, Tarefder, & Syed, 2014; Kasahara, 1982; Timm & Priest, 2005). Blab and Litzka investigated the lateral distribution of heavy vehicles and its effect on the design of pavements. In this study, they used a developed LDM (Lateral Displacement Measurement) system to investigate 27 different sections of road in Austria. The authors discussed and analysed the influence parameters; lane width, rutting, and speed to lateral wheel path distribution. Key findings include; heavy vehicles tend to drive faster in wider lanes, increased speed leads to a concentration of wheel paths, if no rutting is present, lane width is the dominant factor in the lateral shift of the wheel paths (Blab & Litzka, 1995).

Prior research identified the need to better understand wheel path distribution in the US Long-Term Pavement Performance programs. The researchers mentioned that the widely used wheel path definition derived from the LTPP distress manual, with fixed width and position, overlooking the influence of traffic wander in wheel paths (Luo & Wang, 2012). The difficulties of locating the wheel paths on New Zealand LTPP sites has been stated before. It was found that the average wheel path separation could vary from 1600 to 1800mm. This can cause significant problems for surveying vehicles with fixed equipment spacing (Brown, 2005). Multiple studies have investigated the effect of rumble strips and other roadside safety features on the lateral placement of vehicles (Porter, Donnell, & Mahoney, 2004; Taylor, Abu-Lebdeh, & Rai, 2005). The investigation into the effect of centerline rumble strips on the lateral vehicle placement and speed on two-lane rural roads in Pennsylvania showed that rumble strips had a significant effect on the mean and variance of the lateral distribution. The research suggests that the vehicle distributions in the travel lanes may not be normally distributed as previously expected. However, it is also suggested that a larger sample size should be investigated(Porter et al., 2004).

The importance of lateral tracking of vehicles has been determined in several studies(Blab & Litzka, 1995; Luo & Wang, 2013). However, the large majority were conducted under conditions that cannot be compared to modern traffic conditions in New Zealand. Furthermore, most studies internationally have focused on asphalt surface compared to the chip seal over granular base pavements found in New Zealand. Most studies also focus on large highways with relatively high AADT compared to New Zealand state highways. Compared to most studies New Zealand also has a high-speed limit relative to lane and shoulder width.

## 3.3. Methodology

### 3.3.1. Site descriptions

Lateral positioning of traffic was investigated at multiple sites on the State Highway network in the Canterbury Region, west of Christchurch, New Zealand. State Highway 73 (SH73) was chosen as the test site due to the safe test environment created by the relatively low volumes of traffic and long straight segments, providing sufficient visibility of travelling vehicles. This is a two-lane highway with a single lane running in each direction. This site was also chosen as it exhibited the characteristic road markings that are used throughout the Canterbury region. The four sites investigated include one LTPP calibration section, two different straight road segments, and one curved road segment. All sections except for the LTPP section were chosen pseudo-randomly along the feasible length of SH73 within constraints mentioned above.

The LTPP calibration section was a ‘sterile’ test section, meaning limited maintenance has been conducted since the LTPP program’s inception in 2001( T.F.P. Henning 2008). This arguably resulted in a worse conditioned roadway compared to the rest of the highway. The second straight segment was located on a ‘normal’ section outside the township of Darfield, and the third straight segment was located several miles ahead near the township of Kirwee on the same highway. The last two sites had similar road conditions; they were both flat, straight and had similar road features. Both sections were under standard maintenance. Both straight segments had approximately the same lane width of 3.5 meters which is the typical lane width of a New Zealand state highway. The shoulder widths were also similar. The final section was a curved segment located 6 km east of the last straight segment at Annavale Downs.

### 3.3.2. Data collection

The TIRTL was used to determine the lateral positioning of the vehicles. The TIRTL consists of two units, the transmitter, and the receiver. From one side of the road, the transmitter emits laser beams which go to the receiver located on the other side of the road. Vehicles on the road travel through the beams, breaking the continuous connection. The time stamp of the breaking and the re-signal of the laser beam is analysed by the TIRTL software to provide the lateral positioning of the vehicle, along with other information regarding the vehicles, such as the vehicle speed, wheelbase, and axle spacing. The lateral position of vehicles provided by the TIRTL is the distance from the receiver to the vehicle, expressed as a percentage of the distance between the receiver and the transmitter (CEOS-Industrials, 2005). Therefore, to obtain the absolute lateral positioning of the vehicles, all site dimensions were manually measured at all test sites. The information regarding the site location, time and the amount of collected data are shown in Table 10. Due to equipment limitations, it was assumed that the wheel spacing for cars and trucks were 1.6m and 1.8m respectively. However, for the LTPP section, the spacing was considered to be as recorded on site. Calibration of the equipment was carried out once the equipment has been set up. This was done by locating the position of impact using a video camera and comparing that distance to the position reported by the TIRTL. If this was outside the acceptable margin of error, the setup would be re-adjusted.

*Table 10: Time and number of vehicles per site location.*

| *Site Location (SH73)* | *Time* | *Number of Vehicles* |
|---|---|---|
| *Site 1 - LTPP calibration site - Castle Hill* | 12pm to 5pm | 208 |
| *Site 2 - Straight site - Darfield* | 7am to 1pm | 1434 |
| *Site 3 - Straight site - Kirwee* | 1pm to 4:30pm | 396 |
| *Site 4 - Curved site - Annavale Downs* | 8 am to 12 pm | 212 |

### 3.3.3. ESAL calculation

Data were classified into two main categories, heavy and light vehicles, based on the number of axles and axle spacing. All vehicles with two axles and axle spacing less than 3.2m were classified as light vehicles. Also, vehicles with three or four axles and axle spacing between the first two axels being less than 3.2m were identified as light vehicles towing a single axle or a tandem axle trailer respectively, and hence, were categorised as light vehicles (LUK, 2006). All other vehicles not falling within these criteria were categorised as heavy vehicles.

The number of vehicles does not necessarily reflect the damage to the pavement due to the varied nature of axle configuration and loading. Equivalent Single Axle Loads (ESAL) were used as a more reliable approach to characterising the damage to the pavement. ESAL express the degree of damage to the pavement by a single axle group relative to that caused by a standard axle. A standard axle is defined as a single axle with dual tires applying a load of 80kN on the pavement (G. Arnold & Land Transport, 2005). Equation 12 shows how ESAL for a single axle group were calculated.

$$ESAL = \left(\frac{Axle\ Load}{Axle\ Reference\ Load}\right)^n \qquad \text{(Equation 12)}$$

The number of standard axles for the same damage is calculated for a particular vehicle by accumulating the damage of all its axles. The damage from each axle is calculated by dividing the respective axle load by the reference load which is given for each axle configuration and lifting the quotient to the EXP power (Austroads, 1992, 2004). This exponent EXP is dependent on the type of pavement. The power of 4 has been used for more than 40 years, although limitations of the power law have been highlighted (Dawson, 2008). Several authors argued that for thin lightly trafficked pavements a fixed power law the EXP value will need to be larger than 4. A value larger than 7 has been suggested by various studies (Dawson, 2008; Dorman, 1965; Jameson, 1996). For this research, the traditional exponent of 4 was used.

To determine the ESAL for heavy vehicles, they had to be categorised depending on the axle configurations. The TIRTL does not record axles by groups, but provides the number of individual axles and the spacing between each of them. This data was then used to configure the axle groups of each vehicle. Two or more adjacent axles, separated by 2.1 m or less were considered as one axle group as defined by (LUK, 2006).

### 3.3.4. Weigh in Motion (Heavy Vehicles)

The load applied by each axle group of a vehicle is typically determined by a Weigh in Motion (WIM) systems. As the applied loads were not measured on site, the average ESAL values for each class of heavy vehicles was obtained from the New Zealand Transport Agency (NZTA). The data from the nearest WIM site was considered because the heavy traffic composition at this site was assumed to be representative of the chosen sections on State Highway 73.

## 3.4. Results

Figures 27 to 29 show the lateral distribution and confidence intervals of ESAL on the various chip sealed site locations. The traffic direction is shown at the top of each figure (up pointing arrow indicates increasing direction and vice versa). The outer most dashed lines on the plot indicate the edge lines of the pavement, whereas the dashed line in the middle indicates the road centre line. Indicated on top of the plot in each figure is the direction of traffic movement. Figure 27 shows a further two intermediate dashed lines in each lane that show the location where LTPP wheel paths are estimated to lie. The outer most distributions (closed to the edge lines) are recorded while the inside distributions are simulated due to equipment limitations.

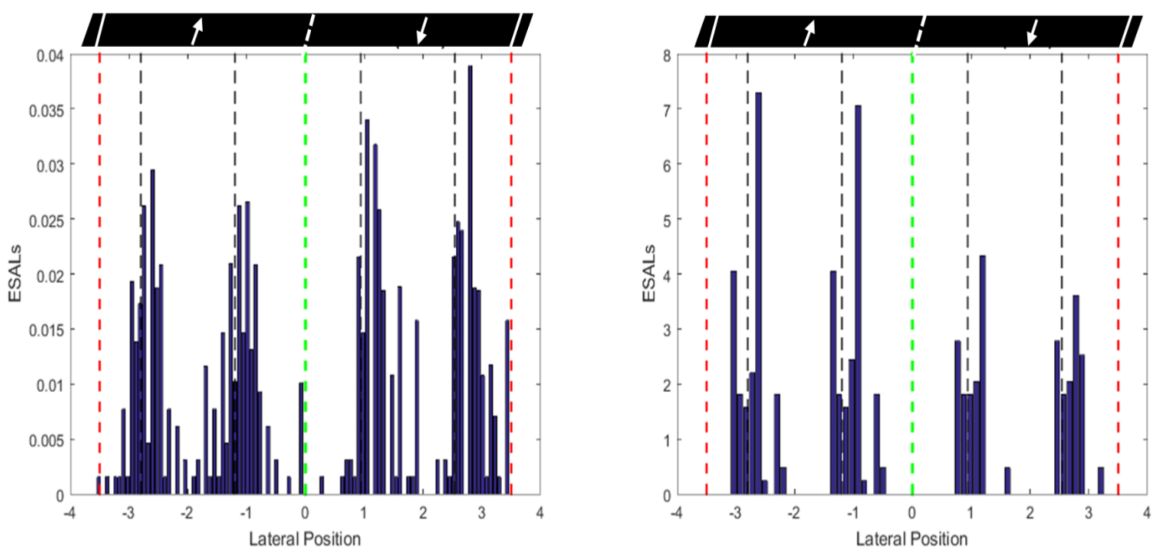



*Figure 27: The lateral ESAL distribution of vehicles at Site 1, the light vehicles are shown on the left (A), the heavy vehicles are shown at the right (B).*

Figure 27 shows a good correlation between the LTPP estimated wheel paths and the ESAL recorded by the TIRTL. In particular, Figure 27B shows agreement between the heavy vehicle wheel paths and the position where the wheel paths are estimated to lie. From this result, it can be concluded that the estimation method employed by NZTA is sufficient for straight sections of road.

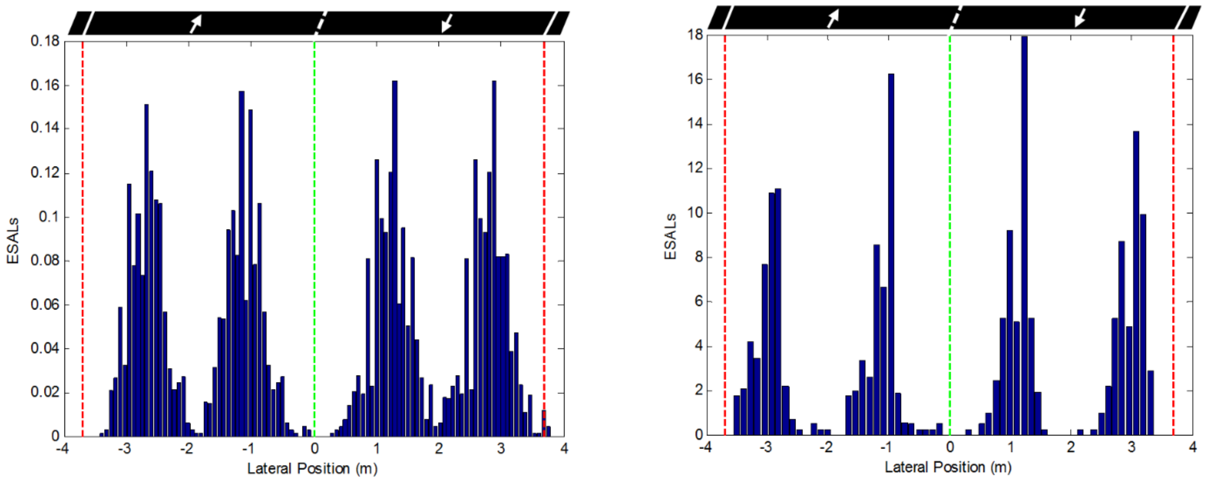



*Figure 28: The lateral ESAL distribution of vehicles at the Site 2, the light vehicles are shown on the left(A), the heavy vehicles are shown at the right(B).*

Figure 28 shows data collected at Site 2. The first major difference between figures 27 and 28 is the number of vehicles recorded. This is shown by the much smoother distributions and the significantly higher ESAL recorded in both the light and heavy vehicle histograms. Figure 28A shows that vehicles classified as light have an ESAL distribution centred around -2.7m for the outside wheel path, increasing direction and -1.1m for the inside wheel path, increasing direction. In the decreasing direction, the outside wheel path is centred around 2.9m and 1.3m for the inside wheel path. Figure 28B shows the ESAL distributions for vehicles classified as heavy vehicles at Site 2. The ESAL distributions are centred around -3.0 m for the outside wheel path, increasing direction and -1.2m for the inside wheel path increasing direction. In the decreasing direction, the outside wheel path wheel path is centred around 3m and 1.2m for the inside wheel path.

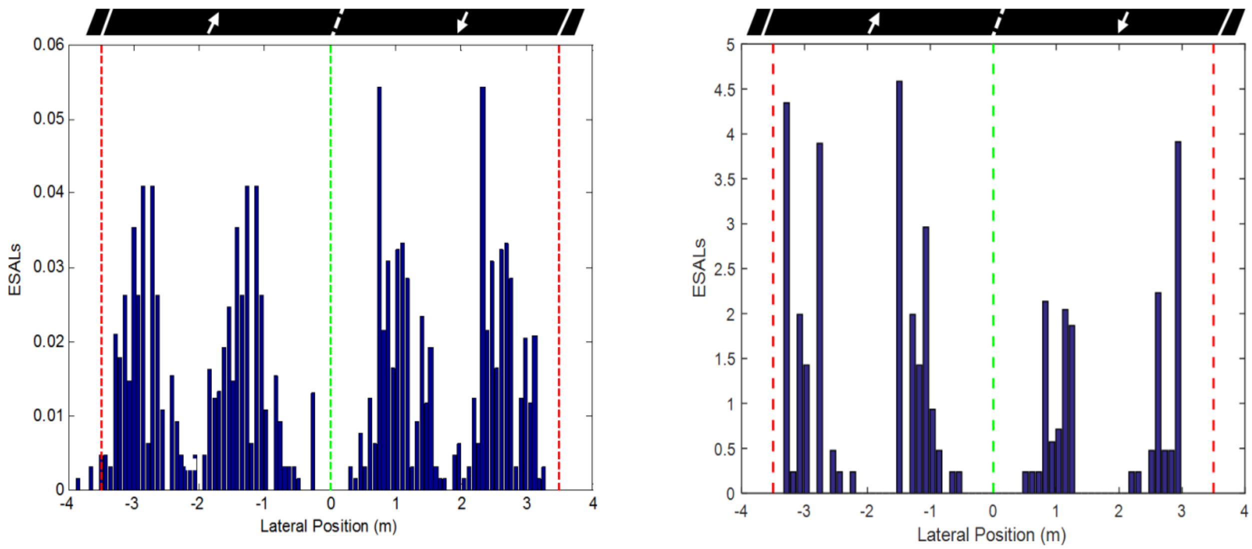



*Figure 29: The lateral ESAL distribution of vehicles at Site 3, the light vehicles are shown on the left(A), the heavy vehicles are shown at the right(B).*

Figure 29 agrees with the positional findings from Figure 28. Figure 29A, however, does show a few vehicles travelling over the edge line which combined with the limited shoulders size, could be a safety concern.

As expected, Figure 27, 28 and 29 show that the ESAL distribution for light vehicles is significantly wider than that of the heavy vehicles. For example, when comparing the ESAL distribution width of the outside wheel path in the increasing direction for light and heavy vehicles, Figure 29 shows a significant difference of 1.5m and 0.9m respectively. It can also be noted that as expected the ESAL peaks is much higher for heavy vehicles than for lighter vehicles. For example, Figure 28 shows that site two's light vehicle ESAL distributions peaked at 0.17 ESAL compared to heavy vehicles peaking at 18 ESAL in the same period.

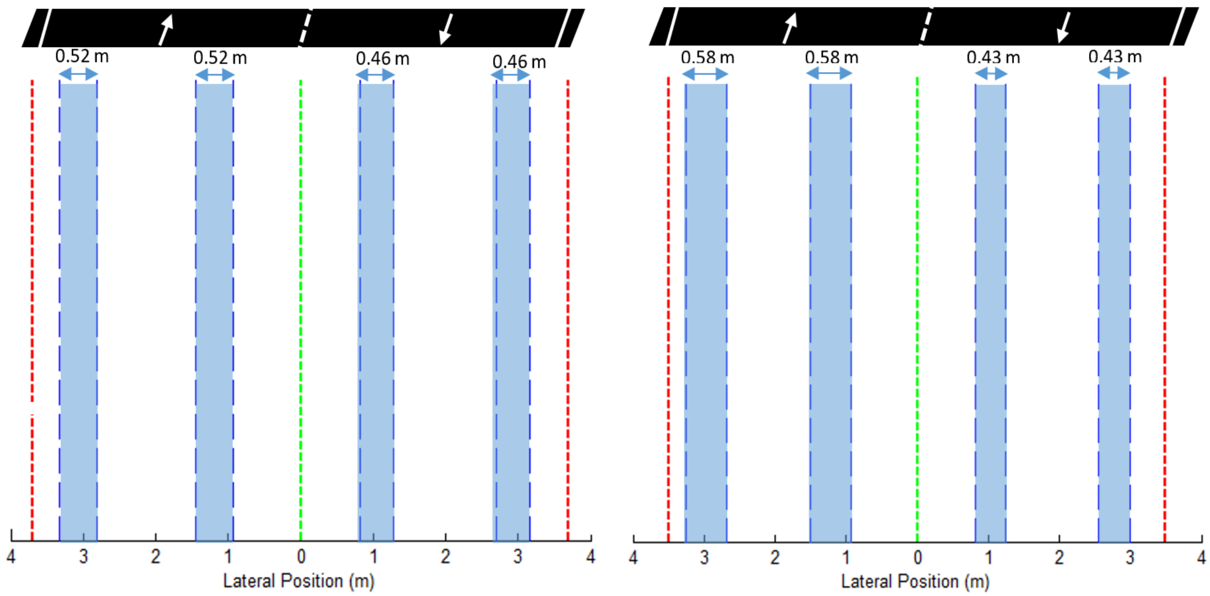



*Figure 30: Lateral position of the wheel paths which includes 75% of the ESAL for Site 2 (left, (A)) and Site 3(right, (B))*

Figure 27, 28 and 29, shows that light vehicles use the entire width of the road on straight sections. These figures also suggest that heavy vehicle ESAL distributions are more concentrated than for light vehicles. To further analyse the results Figure 30 was produced showing 75 % bands of ESAL for sites 2 and 3. It shows that 75 % of the ESAL band is significantly narrower than previous anecdotal design assumptions suggest.

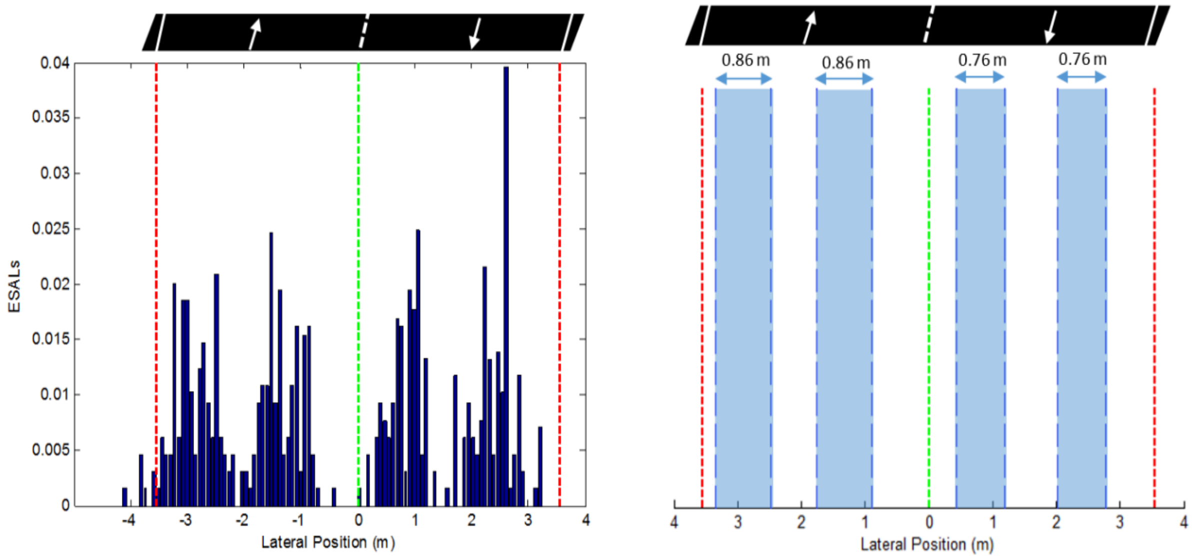



*Figure 31: Left(A), the ESAL lateral distribution of light vehicles at the curve site (Site 4). Right(B), the lateral position of the wheel paths which includes 75% of the ESAL for curve road Segment (Site 4). The direction towards the left is the inside of the road curve.*

The lateral distribution of ESAL of the curved road segment was determined to identify differences between straight segments and curve segments, in terms of positioning and width of the wheel paths. Figure 31 shows this distribution of light vehicles and width of wheel paths where 75% of the ESAL are concentrated. It is evident from this figure that the wheel path distributions are shifted to the left which is the inside of the curve. Also, it is clear that the width of the distribution of the wheel paths is significantly wider than those with the straight segments which means that vehicles do not tend to stay within a confined region of the pavement. As Figure 29, Figure 31 shows more vehicles crossing the edge line, which could be a safety concern due to the small shoulder size.

## 3.5. Bootstrap analysis

To further understand the lateral wheel path distribution a statistical bootstrap analysis was carried out on the Site 2 data set as it contained the largest dataset. In bootstrapping the original sample is treated as the ‘population.’ The ‘population’ is then re-sampled (called a bootstrapped sample), and the bootstrapped sample mean, and standard deviation recalculated. A histogram of the bootstrapped means and standard deviations can then be plotted. These plots can then indicate the variance in the mean and standard deviation of the original sample. The 95% confidence intervals were then calculated. The results are shown in Table 11.

*Table 11: Bootstrapped mean and standard deviation with and 95% confidence interval (CI) for the Darfield straight segment*

| | *Left Lane* | | | | *Right Lane* | | | |
|---|---|---|---|---|---|---|---|---|
| | **Mean(m)** | **95% CI** | **STDV** | **95% CI** | **Mean(m)** | **M95% CI** | **STDV** | **95% CI** |
| *Left Tyre* | 2.98 | 2.89-3.06 | 0.32 | 0.26-0.39 | 1.02 | 0.96-1.07 | 0.25 | 0.20-0.29 |
| *Right Tyre* | 1.10 | 1.02-1.17 | 0.33 | 0.25-0.37 | 2.90 | 2.85-2.94 | 0.24 | 0.20-0.21 |

## 3.6. Discussion

Figures 27 to 29 shows that the cumulative ESAL on a given point of the road is significantly higher for heavy vehicles than light vehicles. It is evident that heavy vehicles are the main contributor of pavement deterioration, despite that they only account for approximately 11% of the traffic composition at the tested sites. Based on that, the pavement deterioration caused by light vehicles could be considered negligible as expected.

The percentage of traffic loading that is included in the wheel path is a critical parameter in determining the width (see Figure 31). There is no established method that specifies which percentage of vehicles limits the wheel path width. If the included percentage of traffic load is too high, the calculated wheel path width would be wider which means loads are not frequently applied on the edges of the wheel path, thus making the edges prone to ravelling. On the other hand, if the percentage of traffic loads included in the wheel path width is too low, the calculated wheel paths would be narrower which means frequent loads are applied outside the wheel paths, making those regions prone to flushing. Hence determining the percentage of vehicles to be included in the wheel path width distribution needs to be optimally chosen by contractors so that both flushing and ravelling is minimised. This problem has been addressed by some contractors that allow electronic control of the spray bar which is able to better match bitumen distribution sprayed on the surface with the lateral wheel path distribution. These contractors are able to utilise the distribution information found in Table 11.

It was seen that the positioning and the width of the wheel paths on a curved road segment were significantly different to those of a straight road segment. Wheel paths were significantly wider and located more towards the inside of the curve. However, in the curved road segment, the testing was conducted only at a single point along the entire width of the road segment. Visual observations suggested that the lateral positioning of vehicles tends to vary along the length of the curve. Therefore, in order to precisely determine the wheel paths in a curved road segment, the lateral positioning of vehicles should be investigated at a number of locations along the length of the curve. Furthermore, the radius and camber of curved roads vary significantly, in addition to the factors mentioned regarding the straight road segments such as the lane and the shoulder width. Therefore, it is unlikely that a generalised result for the location and width of wheel paths could be determined for all curved road segments. However, with extensive testing, location and width of wheel paths could be generalised for curved segments of specified radiuses and cambers. If such a relationship could be generalised, contractors would have to dynamically adjust the bitumen spray bar around each individual corner.

## 3. Recommendations

- Continue work to link lateral distribution of wheel paths to pavement distress and then maintenance procedures.
- Re-evaluate anecdotal pavement design assumptions in light of results presented.
- Continue measurements of different road geometries and characteristics to better understand lateral wheel path distributions on different sections of pavement.
- Investigation of specific pavement distresses on driver behaviour and lateral wheel path position.
- Continued investigation of traffic management implementation on lateral wheel path position.
- Investigate lateral wheel path distributions around curves using multiple sensors.

## 4. Conclusions

This research has demonstrated a methodology that can find the lateral wheel path distribution on roadways in New Zealand. This methodology has been executed on several rural sites around the Canterbury Region. The results show that the method employed by NZTA to find the lateral position to record condition data is sufficient on a straight section of road. The wheel path spacing and width has been analysed and presented for several sites. Using these results contractors are better equipped to calibrate the variable bitumen spry bar thereby prolonging pavement life. Results presented, show that the load concentration in the wheel path is much narrower than original anecdotal assumptions suggests. This impacts pavement design assumptions that presume far more vehicle wander. Preliminary work has been conducted on a curved section. However, more work is needed to understand the lateral distribution of vehicles on curved sections due to the many complexities.

Comments on RAMM data

Discussion with experts in the field identified that the RAMM data was incredibly unreliable. This was due to many factors, but most agree that the RAMM data was not adequate for research as data could not be trusted. It was found that data was often entered incorrectly with respect to geolocation, reported with incorrect units and was considered not trustworthy with respect to 'as built.' RAMM data could still be used on a case by case basis with a major overview. Researchers and engineers must be extremely wary of the problems associated with this data.

# Chapter 4 Specific Site Investigation with the SBMDM

# Purpose of this chapter

This chapter presents research conducted on specific pavement sections around Canterbury using the SBMDM. One of the main benefits of the SBMDM is the ability to investigate pavement data in multiple dimensions. The performance indicator – 'rutting' was found to be the most important performance indicators with regards to pavement deterioration according to experts as shown in chapter 2. Therefore, it was decided that the rutting would be the most important indicator to study.

## 4.1. Introduction chapter 4

In New Zealand, a large percentage of roads are paved with chip seal, designed in accordance with the Austroads design methodology. Chip sealed roads are a cost-effective solution used in the Canterbury region for lower traffic rural state highways. Usually, chip-sealed roads consist of an unbound granular base surfaced with a type of chip seal surface. However, the number of heavy vehicles on rural roads in New Zealand is increasing steadily due to the expanding dairy farming and logging industry. During the period 2006 to 2031, the freight of timber logs, dairy products is anticipated to grow 70% to 75% in terms of tonnes-km transported (P Cenek, Henderson, McIver, & Patrick, 2012). It is therefore important to gain a better understanding of how the combination of an increase in heavy vehicles with this commonly used pavement technique may affect pavement failure.

At present, a significant amount of pavement failure is due to rutting. Rutting is the development of twin longitudinal depressions along the wheel paths which is mainly caused by progressive movement of materials due to repeated loading (Tarefder, Zaman, & Hobson, 2003). Depending on the magnitude of the traffic load and the relative strength of the pavement layers, rutting can occur in the surface, subsurface and subgrade layers or in a combination of these layers. Because the chip-seal surface is thin, rutting in chip-sealed roads is commonly caused by mechanical deformation in subsurface layers (D. D. Gransberg & James, 2005), which in itself is generally an indication of an overloaded pavement.

In pavement design, the recognised terminal rut depth seems to be 20-25 mm (B Pidwerbesky, 2014). Note that rutting is measured using the worst affected area, or the deepest rut of the two wheel paths as it concerns a safety aspect. Observations of pavements indicate that rutting occurs more in the outside or left wheel path (LWP) than in the wheel path closest to the middle or crown of the road, the right wheel path (RWP). If rutting happens more in the LWP than the RWP, it is of interest to know why this happens. Note that in New Zealand, the traffic drives on the left.

It is important to note that in the current design process there are no allowances put forward for a difference in load on the left and right wheels of an axle. Most design criteria and road regulations simply assume that each wheel load equals 50% of the axle load. This is also the case in New Zealand, where municipalities and highway organisations set out maximum axle weights or truck weights, and maximum wheel loads, whereby the maximum wheel load equals half of the maximum axle load. Finally, to help drain water off the road, the use of camber or cross-fall of approximately 1-3% is common in pavement designs, as is the case in New Zealand.

### 4.1.1. Research objectives

The research presented in this chapter examines the observed difference in rutting that occurs on the outside and the inside wheel paths. Rutting data from two rural sites supplied by the New Zealand Transport Agency (NZTA) is used to verify the assumption that rutting occurs more often on the outside wheel path. Subsequently, leading causes for rutting from literature are briefly discussed with respect to their contribution to the differential rutting. Then, using a free body diagram, the effect of camber on the distribution of the vehicle weight between the left and right wheels is calculated. The damaging effect of heavy vehicles on pavement in combination with standard pavement camber will be further investigated using a calculation example. The focus of the research is on chip-sealed roads in Canterbury, New Zealand. The data comes from sterile Long-Term Pavement Performance (LTPP) sections monitored by the NZTA. In this context, sterile LTPP sections are sections of road that have undergone only emergency maintenance work since the inception of the LTPP program. The used sections are located within feasible driving distance for visual inspection.

After briefly summarising related research, the methodology is highlighted, which includes a detailed description of the data. In the results, the contextual data and traffic data from the road sections will be given followed by the rutting data. The actual difference in rutting will be analysed, and by calculating the equivalent standards axles (ESAL), the different magnitude of the damaging effect on the left and right wheel paths can be shown. Finally, the results will be discussed, which is followed by a brief conclusion.

## 4.2. Literature review

Rutting on the surface is most commonly caused by deformation in the subsurface layers of the pavement's structure for chip sealed roads (D. D. Gransberg & James, 2005). Several factors contribute to the subsurface deformation. Firstly, there are environmental factors like weathering of materials, excess pore water pressure, freeze-thaw cycles and excessive temperature variations (Adlinge & Gupta, 2013). Secondly, there are pavement design and geometric factors.

Examples of design factors are compaction, depth, and makeup of sub-layers, the ability of the subgrade to resist any permanent deformation(Gribble, Patrick, & Land Transport, 2008) and limited edge support (Aksnes, Hoff, & Mork, 2002; G. K. Arnold, 2004). Pavement geometric factors refer to, for example, quality of materials. Thirdly, there is the traffic-loading factor.

Which of these factors contribute most to rutting is debated in (Hicks, Moulthrop, & Daleiden, 1999), who stated that both rutting and depressions were primarily caused by loading. Similarly, Saleh and Patrick (2006) in a study on pavement shoulders found that that axle load was the most significant factor affecting the deflection and strain at the locations tested. Although loading can be further specified into magnitude, repetitions and loading speed (Fwa, Tan, & Zhu, 2004), generally it was found that especially higher magnitudes of traffic loads subjected pavement sections to higher deflections (G. K. Arnold, 2004; M. F. Saleh & Patrick, 2006; Transit-New-Zealand, 2007; Tutumluer & Pan, 2008; Zaghloul & Holland, 2008).

Few authors discussed the difference in rutting between the wheel paths. However, Chen and Hugo (1998) conducted experiments highlighting the difference in deflection between the wheel paths. They used the Texas Mobile Load Simulator to show that the LWP had higher FWD deflections than the right wheel path (RWP), and consequently, the LWP manifested more rutting in HMA surface. In their experiments, they primarily attributed that to differences in moisture content. More recently, research was conducted on ruts in asphalt pavement on multi-lane Lithuanian highways (Sivilevičius & Vansauskas, 2013). It revealed that rutting was most severe in the outside lane where heavy vehicles travel most often.

In New Zealand, research concerning rutting mostly went into either rut progression over time (G. Arnold, Werkmeister, & Alabaster, 2008; Collins &

Boulbibane, 2000; Theuns Henning, Dunn, Costello, & Parkman, 2009; T. F. Henning, S. Costello, & T. Watson, 2006; T. F. Henning et al., 2004) or into the relationship between rutting and vehicle safety. The difference in loading between the left and right wheels caused by camber in the road has been used in safety-related research involving heavy vehicles and vehicle rollovers. Here, the difference in loading between the left and right wheel paths were observed and this observation was subsequently used to improve safety. Based on an extensive literature review, no research was found that specifically targeted the differences between the RWP and LWP rutting, on chip-sealed roads.

## 4.3. Methodology

### 4.3.1. LTPP data

Two Long-Term Pavement Performance (LTPP) sites in Canterbury New Zealand have been used for this research. The LTPP programme was established in New Zealand to record accurate pavement data. Since the sections became part of the LTPP network, no maintenance has been performed on them other than safety-related maintenance. Contractors regularly measure various performance characteristics of the pavement and upload the data into the LTPP database. The LTPP data consist of inventory, as-built, traffic, strength, maintenance, and condition data. The LTPP condition data contains the rutting data; This data is measured yearly by a purpose-built tool that is designed to measures the rut on both wheel paths to an accuracy of ± 0.2mm resolution on chip seal roads. The measurements are taken and calculated every 10 m along the 300-meter section (Brown, 2005). More detailed information on the used set up can be found in (T. Henning & D. Roux, 2008). Next, to complete the overall view of the context of the two sections, data from other databases containing weather, traffic, and pavement construction data was collected utilising the SBMDM.

### 4.3.2. Statistical methods and ESAL calculations

After collection of the relevant information, the rutting data will be analysed to verify whether the rutting in the outside (LWP) and inside wheel paths (RWP) are significantly different, computing the mean and standard deviations. Although the mean can be skewed by extreme values, it will be used as the measure of “centre” for the research. This can be done because there are minimal outliers in the data. Hence, the mean will be more appropriate than the mode or median.

### 4.3.3. Calculating the damaging effect of loading

After data analysis, the effects of camber on load distribution between the wheels will be examined using a simple free body diagram. The difference in wheel loads is then calculated into ‘ESAL’ to quantify the difference in damage to the pavement. In calculating the damage from traffic loading on the pavement, the equivalent number of standard axles (ESAL) is normally used. The standard axle is a single axle with dual tires that applies an axle load of 80kN to the pavement. Actual traffic loadings are transformed using Austroads Equivalent damage equation.

The damage from each axle is calculated by dividing the respective axle load by the reference load which is given for each axle configuration and lifting the quotient to the EXP power(Austroads, 1992, 2004). This exponent EXP is dependent on the type of pavement. The power of 4 has been used for more than 40 years, although Dawson (2008) highlighted limitations of the power law. Several authors argued that for thin lightly trafficked pavements for a fixed power law the EXP value will probably need to be larger than 4. In fact, a value larger than 7 has been suggested by various studies (Dawson, 2008; Dorman, 1965; Jameson, 1996).

## 4.4. Results and analysis

### 4.4.1. Pavement section description

The first section CS-42 is located on hilly farmland. The road itself is, along part of its length, set against a small hill bordering a flat stretch of land. A section of the road borders a hill in such a fashion that there is a possibility of water runoff into the pavement structure. This straight section of road on state highway 74 sits on average 706 m above sea level with a difference between start and end elevation of 6.4 m.

The second section, CS-44 is located in flat terrain with some rolling hills, minimal vegetation close to the road, partly situated on a gradual bend on a reasonably flat area of state highway 8. The difference between start and end elevation is 1.8 m, with an average height above sea level of 768 m. Table 12 shows more details on the sections. The roads in question have been constructed prior to the start of data acquisition in 2002.

*Table 12: Details of road sections CS-42 and CS 44 in Canterbury New Zealand.*

| DETAILS | SECTION CS-42 | SECTION CS-44 |
|---|---|---|
| **DATA AVAILABILITY** | Years 2002-2014 | Years 2002-2014 |
| **SEGMENT** | 300 m of 2-lane rural highway | 300 m of 2-lane rural highway |
| **RAINFALL** | 1632mm/y | 261mm/y |
| **TEMPERATURE** | - 10 to 35 C | - 10 to 30 C |
| **PAVEMENT** | Two Seal Coat Bitumen Bound Chip seal | RE-Seal Bitumen Bound chip seal |
| **BASE THICKNESS** | 130 mm | 110 mm |
| **SUB-BASE THICKNESS** | 180 mm | 300 mm |

| | | |
|---|---|---|
| **SUBLAYERS MATERIAL** | Sandy gravel base on in situ rocky clay | AP40 base on in situ sandy gravel |
| **OBSERVED DAMAGE** | • Edge of pavement showing significant damage due to ravelling and edge cracking.<br>• Potholes and bleeding present in both wheel paths in both directions.<br>• Some patches of severe rutting.<br>• Seal is extremely thick in places especially close to the edge | • Edge cracking repairs completed recently.<br>• Very narrow shoulders in some parts.<br>• No excessive ravelling or bleeding in the wheel paths.<br>• Seal is thick in some places |

Both sections are on trucking routes but also carry a significant proportion of light vehicles from tourists and destination traffic. Table 13 shows the annual average daily traffic for the sites.

*Table 13: Percentage traffic data for LTPP section CS-42 & CS-44 (NZ LTPP)*

| SECTION ID | AADT | CARS | LIGHT COMMERCIAL VEHICLES & BUSSES | HEAVY VEHICLES (HV) |
|---|---|---|---|---|
| **CS-42** | 1351 | 87% | 2% | 11% |
| **CS-44** | 1230 | 85% | 2% | 13% |

## 1.1 Rutting data

In Figure 32 and 33, the mean rutting depths for the two sections are shown for each wheel path per year. Note that the left wheel path (LWP) is the wheel path closest to the shoulder, the right wheel path (RWP) is closest to the middle or crown of the road. The graphs show clearly that the rutting on the left wheel path is more pronounced than the rutting on the right wheel path. In addition, the difference in rutting between left and right wheel path generally increases over time. At section CS-44 the right wheel path rutting remains relatively constant, while at section CS-42, the rutting increases over time although much less than the left wheel rutting.

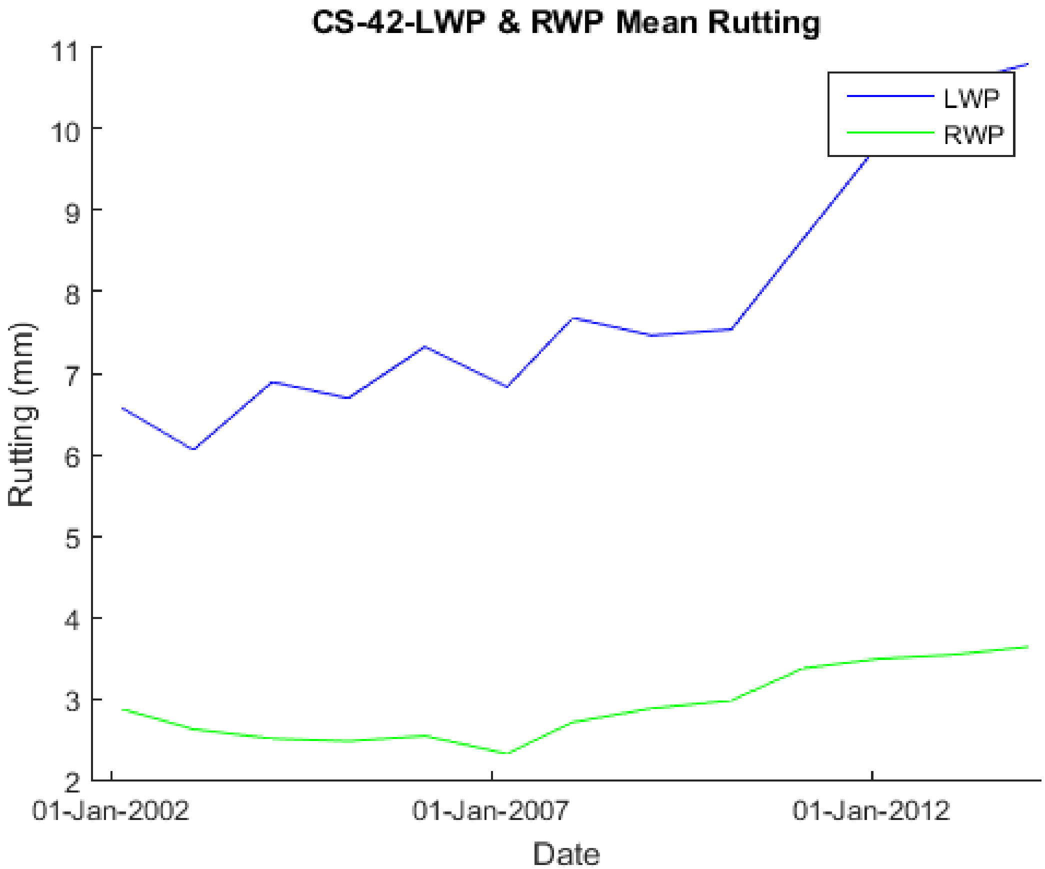



*Figure 32: Measured mean rutting depths for left wheel paths and right wheel paths (LWP resp. RWP) for sections CS-42*

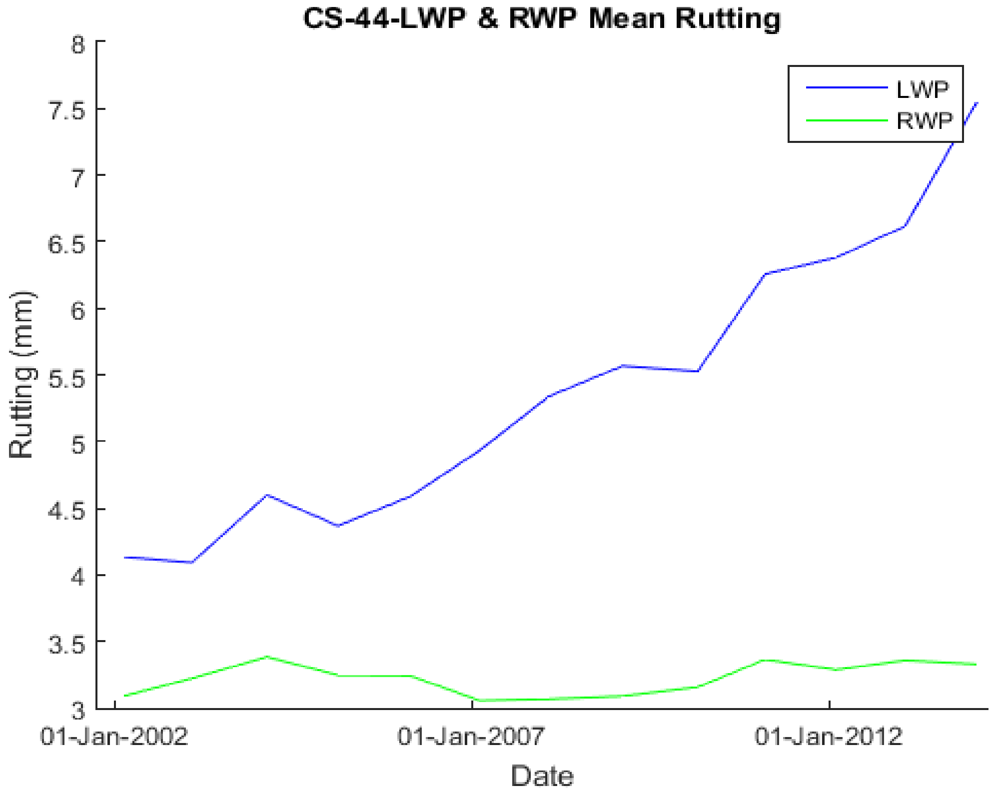



*Figure 33: Measured mean rutting depths for left wheel paths and right wheel paths (LWP resp. RWP) for section CS-44, yearly data from 2002 to 2014.*

Figure 34 and 35 displays the standard deviation of the rutting depths for each wheel path per year. At section CS-42, the data suggests that the standard deviation of the rutting depths increases more for the RWP than the LWP. At section CS-44, the standard deviation of the right wheel path seems stable, while the rutting of the left wheel path increases over time. Figure 34 does show a general increase in the cumulative standard deviation of rutting depths as the years progress.

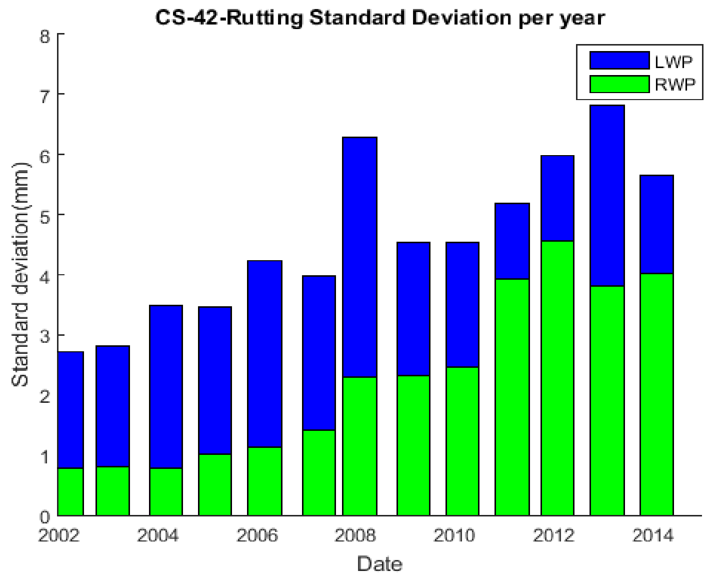



*Figure 34: Standard deviation of the rutting depths for left wheel paths and right wheel paths (LWP resp. RWP) for sections CS-42*

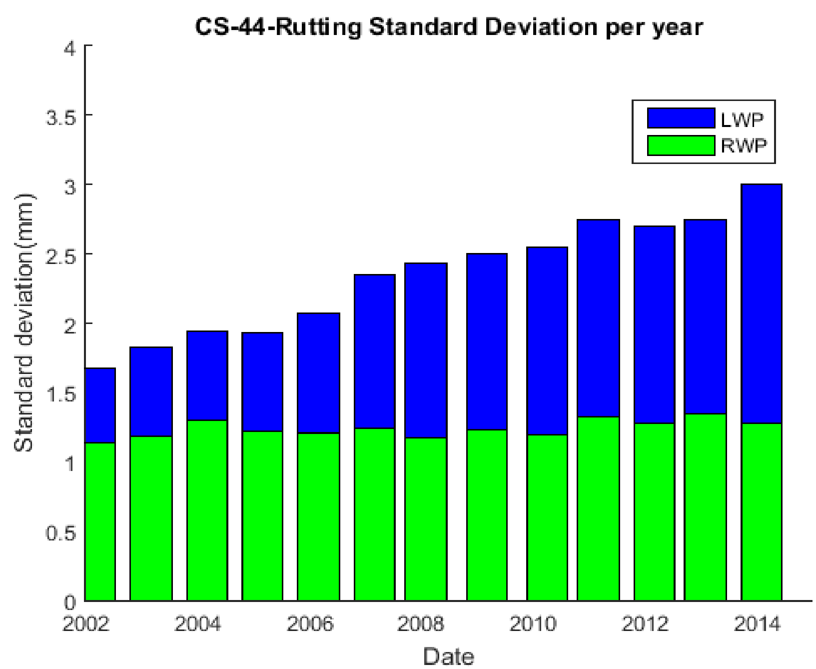



*Figure 35: Standard deviation of the rutting depths for left wheel paths and right wheel paths (LWP resp. RWP) for section CS-44, yearly data from 2002 to 2014.*

## 4.4.2. Effects of camber on load distribution

There are various equations and free body diagrams which can be used to calculate the Static Rollover Threshold (SRT)(Ivan & Ossenbruggen, 2000; Milliken & de Pont, 2004; Winkler & Ervin, 2000). The calculation of the SRT, the location, and direction of the gravity vector has to be established. A similar process is used here to find the difference in loading between left and right wheel. Figure 366 shows a free body diagram for a truck on a straight road with camber (camber exaggerated in the drawing).


*Figure 36: Static analysis of camber effects on the axle.*

Analysis of the simplified static free body diagram in Figure 36 of a heavy vehicle on the road with camber, shows that the force required to support the axle (forces $P_1$ and $P_2$) will be larger on the outside, the left wheel path ($P_1$) than the inside or right wheel path ($P_2$). This is due to the fact that the centre of gravity is positioned at height H above the pavement, which makes the gravity vector go through a point other than the midpoint between the wheels. In this example, the vector goes through a point closer to the left wheel, which increases the load of that wheel on the pavement.

Equation 13 through 16 give the load that corresponds to the left wheel ($P_1$), and the right wheel ($P_2$) respectively.

$$F = M_c g \cos(\theta) \qquad \text{(Equation 13)}$$

$$P_2 = \frac{F(-2\mathrm{H}\tan(\theta) + C)}{2c} \qquad \text{(Equation 14)}$$

$$P_1 = F - P_2 \qquad \text{(Equation 15)}$$

$$\frac{\mathrm{P}_1}{\mathrm{P}_2} = \frac{\cos(a-\theta)}{\cos(a+\theta)}\,, \quad \text{where } a = \tan^{-1}\left(\frac{2H}{C}\right) \qquad \text{(Equation 16)}$$

Where *C* is the width of the axel (m), *H* is the height of the centre of gravity of the truck above the pavement (m), and $\theta$ represents the camber in radians. In New Zealand, on flat stretches of roads, the design of pavements uses a camber that ranges between 1-3% (~0.01 - 0.03 rads). It follows from the equations that realistically the most important variable affecting the ratio of $P_1$ to $P_2$ is the height *H,* while width *C* is bound by the width of the road. As *H* increases, the difference in loading between left and right will increase.

The effect of the differential load can be illustrated by calculating the damage of a typical milk truck in New Zealand using the method described in Austroads (2007). Here the damage caused by a vehicle is expressed as the number of equivalent standard axles loads (ESAL) which produces the same amount of damage.

The characteristic axle and wheel configuration for a milk truck in New Zealand is a 4-axle truck and 4-axle trailer with a gross vehicle weight (GVW) rating of 44 tonnes and maximum overall length of 20m. The loading on each axle group is 3.96 tons per tandem axle single tire (TAST) and 6.13 tons for per tandem axle duel tire (TADT). This is divided by the reference load, respectively 9.2 and 13.8 tonnes and lifted to the $4^{th}$ power(P Cenek et al., 2012). A milk truck has one TAST and three TADTs so using Equation 17, the standard calculation of ESAL of a milk truck results in 2.30 ESAL.

$$ESAL = \left(\frac{\text{TAST} + \text{TAST}}{\text{Equal Damage TAST}}\right)^4 + 3 * \left(\frac{\text{TADT} + \text{TADT}}{\text{Equal Damage TADT}}\right)^4 \quad \text{(Equation 17)}$$

These 2.30 ESAL are based on the load spread evenly over the left and right side of the axle, with each wheel causing the same amount of damage. However, if Equations 13- 16 are used with a camber of 3%, then it follows that approximately 54% of the load is carried by the left wheel and 46% by the right wheel. If the loading on the left wheel is used to calculate the damaging effect, this would be equivalent to an ESAL number of 3.0. Likewise, the lower load on the right side would indicate an ESAL of 1.7. Although the ratio of loads is only 54%/46% (=1.17), the ESAL show a ratio of $(0.54/0.46)^4$=1.90. This ratio indicates that the left wheel would cause significantly more damage than the right wheel, even when a slight (3%) camber is used.

The camber calculation example was a static analysis and did not include the effects of the dynamic behaviour of vehicles, nor the effects of existing differential rutting on the increase of the effective angle. Furthermore, no vehicle details have been taken into account like shock absorbers, which can amplify the camber effect, therefore increasing the load in the LWP. Pavement imperfections like potholes and pothole repairs have not been taken into account either.

These different ESAL values can be used for the calculation of the total ESAL per year by heavy trucks per section (Table 3). At present, the AADT of heavy traffic on sections CS-42 & CS-44 (Table 14) is multiplied by 2.3 ESAL (using averaged wheel loads). Subsequently, the left wheel load (3.0 ESAL) and the right wheel load (1.7 ESAL) are used to calculate the equivalent yearly ESAL's.

*Table 14 : Applying different loading distributions to calculate ESAL for LTPP sections CS-42 & CS-44.*

| **SECTION** | **CS-42** | | **CS-42** | |
|---|---|---|---|---|
| **LOADING DISTRIBUTION** | Heavy Vehicles per year | ESAL per year | Heavy Vehicles per year | ESAL per year |
| **AVERAGE WHEEL LOADS** | **54,243** | **124,758** | **58,364** | **134,236** |
| **LEFT WHEEL LOAD** | 54,243 | 162,728 | 54,243 | 175,091 |
| **RIGHT WHEEL LOAD** | 54,243 | 92,212 | 54,243 | 99,218 |

From table 14 it is obvious that there is a significant difference between the yearly ESAL outcomes for the sections depending on which load calculation is used. The bold, top line shows the calculation that is used at present, using axle loads. The two rows below show the ESAL on the LWP respectively RWP. The amount of damage to the pavement can be expected to differ significantly as one side carries more and more of the load as the rut deepens. This difference between LWP and RWP will be amplified when a larger exponent say 7 is used in the calculation of ESAL as suggested by Dawson (2008). This would result in an ESAL ratio of $(0.54/0.46)^7 = 3.1$.

## 4.5. Discussion

Pavement performance is affected by environmental factors, design geometry, and loading factors. Environmental effects like excessive pore pressure due to the increase of load reduce the effective stress between particles, which can result in permanent deformation of the in-situ subgrade soil and base course. Section CS-42 experiences more rainfall annually than CS-44 and the rutting depths at section CS-42 were larger than CS-44.

Another possible contribution to the increase of rutting in the LWP is the effect of weathering of the base course. Weathering is a long-term degradation of aggregate structural properties due to oxidation. Due to the permeable nature of chip seals, it is important for water to drain away from the base course and slow the effects of weathering. However, drainage is not always effective as vegetation can hinder it and small particles such as clay can prevent the water close to the base course. Due to the dynamics of diffusion, this effect will be most noticeable closer to the edge of the road and therefore closer to the LWP. Section SC-42 has a high annual rainfall more vegetation close to the pavement edge, which could result in higher weathering rates of the outside region of the pavement structure.

A significant change in temperature could also have led to an increased amount of weathering in the base course under the LWP. Large changes in temperature can fracture the aggregate. The introduction of moisture increases this effect. Freeze-thaw cycles can damage and degrade the base coarse aggregate. Both sections examined are above 700m in alpine conditions where air temperatures often go below zero in winter and above 25 C in summer with the occasional snow and snowmelt. This may have weakened the sub-layer materials and resulted in excessive rutting. Snowmelt, in particular, will increase the moisture content in the local surrounding environment for extended periods, further increasing the amount of saturation in the outer edge of the base course.

The pavement geometry in New Zealand normally has a limited shoulder size, which is present on both CS-42 and CS-44. Lateral components of loads applied to the wheel path push outward. Lateral stress in the direction of the centreline is well supported. However, due to the limited shoulder, the lateral stress pushing towards the road edge is poorly supported. This could allow increased movement to occur resulting in deeper rutting in the LWP.

Limited shoulder width contributes to edge cracking close to the LWP. Cracks close to the LWP allow further water infiltration into the base course, which could amplify pore water pressure, weathering, and loss of base material. CS-44 has had emergency edge repairs, which may have created discontinuities between the original seal and the repaired section.

However, loading has been shown to be the most influential factor on rutting in chip-sealed roads. A brief calculation showed that the effect of camber on transverse load distribution leads to significant differences even at cambers of 3%. This would be amplified further if an exponent 7 were used as opposed to 4 in ESAL calculations as suggested by Dawson (2008).

## 4.6. Conclusion

This research involved a detailed assessment of two sections of road in New Zealand where pronounced differences between rutting depths in the left and right wheel paths were present. The rutting on the right wheel paths was consistently shallower than on the left wheel path. A free body diagram illustrated that camber could give rise to a shift in loading from the right to left wheel. This shift in loading can cause a significant change in ESAL calculations.

It is plausible that the difference in loading between left and right wheels contributes to a difference in damage to the pavement. As mentioned in literature, water impinging from the outside could also attribute to differential rutting progression, as can the limited edge support of the New Zealand Roads. The present research has not been set up to distinguish between these three factors. Nevertheless, it seems that loading plays an important role, if not alone than in combination with the other two factors. With the increase of heavy vehicles to come in the future, the increase in ESAL can be expected to continue, increasing the damage to the pavement further. It is recommended that further research be conducted at the network level.

# Chapter 5 Network Investigation with SBMDM

# Purpose of this chapter

Following the recommendations from Chapter 4, the SBMDM tool can be further demonstrated by showing an investigation of pavement data at a network level. This involves investigating data in a different dimension of the of the SBMDM as shown in chapter 2. This chapter covers similar topics as that from chapter 4 as both chapters are focused on rutting. However, this chapter details a study view rutting data from a holistic viewpoint rather than specific locations.

## 5.1. Introduction - chapter 5

A rut is a progression of longitudinal depressions along the wheel paths which is mainly caused by progressive movement of materials due to repeated loading (Tarefder et al., 2003). Currently, rutting is a significant problem that can lead to pavement failure. With respect to asset management, rutting can be an indication of an overloaded pavement. Rutting can occur on the surface, subsurface and subgrade layers or in a combination of these layers depending on their strength and magnitude of the load applied. Because chip-seal surfaces are thin, rutting in chip-sealed roads is commonly caused by mechanical deformation in subsurface layers (D. D. Gransberg & James, 2005).

Rutting is one of the most widely used pavement performance indicators for thin flexible pavements. It is important for a number of reasons. Firstly, it is important from a safety point of view. For safety reasons the recommended rut depth should not exceed 11mm(Lay, 1998) to 25mm(Ong, Pasindu, & Fwa, 2012) based on road geometry, road class, surface type and vehicle speed. This could lead to an increased risk of water ponding which could lead to hydroplaning, loss of control and insufficient breaking distances. To help drain water off the road, the use of camber, cross-fall or crown of approximately 1-3% is common in pavement designs. Secondly, rutting is an important performance indicator and trigger mechanism in Pavement Management Systems (PMS). In most PMS systems rut depth or some form of rutting index is used as part of a trigger criterion for future intervention and  maintenance(Robinson, Danielson, & Snaith, 1998). Rutting is measured using the worst affected area, or the deepest rut of the two wheel paths. (PD Cenek, Henderson, Forbes, Davies, & Tait, 2014; Hicks et al., 1999). Lastly, rutting is commonly used as design criteria in pavement design processes. In pavement design, the recognised terminal rut depth seems to be 20-25 mm (B Pidwerbesky, 2014). According to Austroads design handbook, the critical trigger depth of 20mm is assumed to be the failure point in the subgrade for thin flexible pavements (Austroads, 1992, 2004).

In most pavement design criteria, it is assumed that each wheel carries 50/50 of the axle load and there are no allowances put forward for a difference in load in the wheel paths. Municipalities and high way agencies set out maximum axle and truckloads. The wheel loads are assumed to be 50% of the maximum axle load. From previous research conducted by (van der Walt, Scheepbouwer, & Tighe, 2016) it was found that with camber a significant amount of load is shifted to the outside wheel path. This can significantly change the number of ESAL experienced by the left and right wheel path as will be discussed in the next section.

### 5.1.1. Observations and free body diagram from previous research

Observations of pavements in Canterbury, New Zealand indicate that rutting occurs more in the outside or left wheel path (LWP) than in the wheel path closest to the middle or crown of the road, the right wheel path (RWP).  Research done by (van der Walt et al., 2016) shows that this effect is not as minimal as would have originally been predicted. Using the free body diagram, it can be shown using the example of a milk truck (common due to the large dairy industry in NZ) that the effect of camber would cause significantly more load in the LWP than the right, even when a slight (3%) camber is used.

### 5.1.2. Rutting deterioration phases

It has been widely accepted that pavement deterioration can be broken up into three main stages as shown in Figure 37. This holds true for rut progression. Firstly, Phase 1, an initial densification/ consolidation stage straight after construction that continues for a relatively short period. Secondly, Phase 2, a stable rut progression where relative constant rate deterioration occurs for an extended period of time. Lastly, Phase 3, an accelerated rut progression rate, which represents rapid deterioration towards the end of the pavement's design lifecycle.

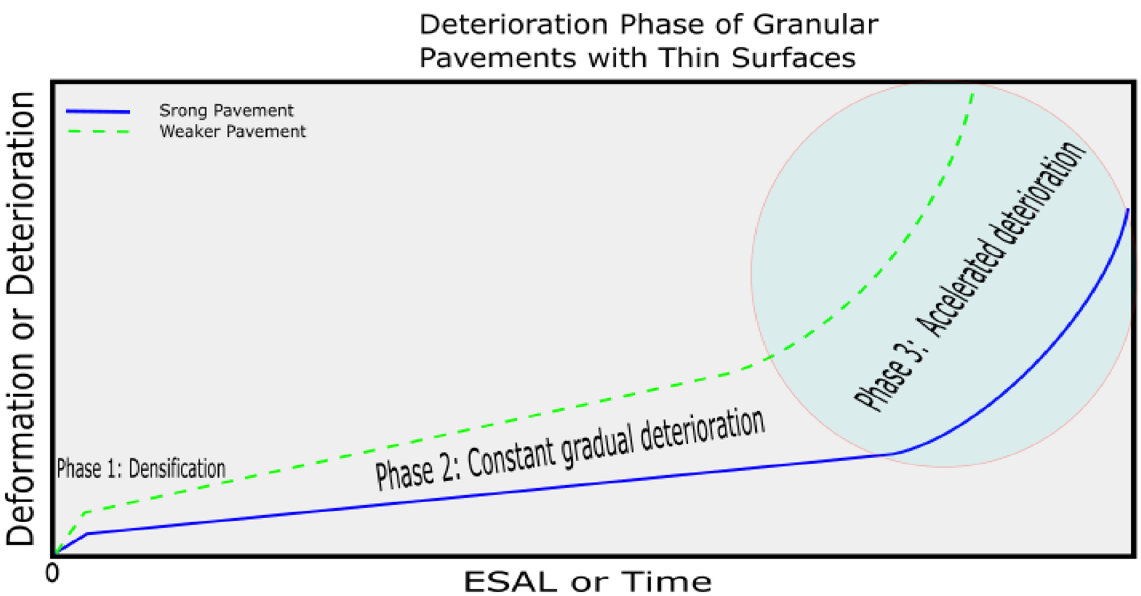



*Figure 37:Deterioration Phases of Granular Pavements with thin surfaces Adopted from(Martin, 2003)*

While many methods exist that allows for predictive capability (HDM-4 models and (Martin, 2003)), Henning et al. 2009 conducted research that showed a new approach for modelling rutting that was the most relevant for New Zealand conditions. Their research follows the three-stage modelling approach as discussed. The first is a simplified model to predict the initial densification/ consolidation. The second is a linear model to predict the progression of rutting during the relatively stable rut stage. Finally, a model is used to predict the probability of a pavement undergoing accelerated rut progression associated with failure of the pavement (Theuns Henning et al., 2009). It was determined by researchers that the first Phase was only a factor of SNP as further discussed by Henning et al. 2009.

Phase 2 model is outlined in Equations 18 and 19.

For thin pavements (<150mm):

$$RPR = 9.94 - 1.38 \times a_1 SNP \quad \text{Equation (18)}$$

For thick Pavements (>150mm):

$$RPR = 14.2 - 3.86 \times a_1 SNP \quad \text{Equation (19)}$$

$Where$:

$RPR = stable\ rut\ progresion\ rate \left(\frac{mm}{10^6 ESAL}\right)$

$a_1, a_2 = Calibration\ factors$

$SNP = Modified\ Structural\ number$

Phase 3 of Henning et al. 2009 model is arguably the most important. Phase 3 gives a probability of accelerated rutting all the way from construction to end of life as shown in Figure 37. This gives us a probability of when intervention should take place dependant on ESAL or Time.  Hennings et al. probabilistic model for accelerated rutting is shown in Equation 20. Accelerated rutting is defined to have occurred when the rutting rate reaches twice the expected stable progression rate. In New Zealand, the stable rut rate is considered between 0.4 to 0.6 mm per year (T. F. Henning, Costello, Watson, & Land Transport, 2006).

$$P(Rut_{Accel}) = \frac{1}{1 + \exp(-7.568 * 10^{-6} * ESAL + 2.434 * SNP - P.T.F.)} \quad \text{(Equation 20)}$$

*where*:

$ESAL = Number\ Equivalent\ Standard\ Axel$

$SNP = Structural\ Pavement\ Number$

$PTF = Pavement\ thickness\ facor. For$ base layer thickness $< 150$ mm, $PTF = 4.426$ & $For$ base layer thicknes $> 150$ mm, $PTF = 0.4744$

Both Phase 2 and Phase 3 models were calibrated against CAPTIF program data (Canterbury Accelerated Pavement Testing Indoor Facility) located in Christchurch Canterbury(Theuns Henning et al., 2009). This facility consists of a 58m long circular track containing 1.5m deep by a 4m wide concrete tank. On top of the trail pavement structure sits a simulated load and vehicle emulator (SLAVE) that runs around the circular track. This allows researchers to control conditions for pavement construction and deterioration measurements precisely (Alabaster, Fussell, & Land Transport, 2006; B. D. Pidwerbesky, 1995).

## 5.2. Scope and objectives of this chapter

- This Chapter will investigate the rutting progression across the New Zealand Long-Term Pavement Performance program (LTPP) in terms of the differences in LWP and RWP rutting.
- This Chapter will explain this difference by showing that there is a cost to camber in terms of rutting deterioration in the left and right wheel paths. The specific investigation into the Phase 2 and Phase 3 accelerated rutting of the left and right wheel path will be conducted.
- It will be shown that the due to camber there is a higher likely hood that the LWP will fail before the RWP over time.
- Models, results, and limitations will be discussed.

## 5.3. Method

### 5.3.1. LTPP Data used for this study

All available sterile Long-Term Pavement Performance (LTPP) sites in New Zealand have been used for this research. The programme monitors a number of 300 m long sections of roadway across New Zealand. These sections (called calibration sections) together form a representative sample of the New Zealand road network. This research will focus on sterile sections to limit variability introduced by maintenance. Consultants measure various performance characteristics of the pavement annually, and upload the data into the LTPP database.

### 5.3.2. Analysis method

Using all the sterile data in LTPP all pavement calibration sections will have the LWP, and RWP data analysed. The maximum rut depth will be the most important followed by the mean and minimum rut depth. From a maintenance point of view, the maximum rut depth is a safety concern. The mean and minimum rut depth is also important as it gives an idea of rest the population.

### 5.3.3. Deterioration modelling

Henning et al. model for accelerated rutting give us the probability of accelerated rutting. We know that the model was calibrated against the CAPTIF data where the load was not controlled by camber but precisely controlled by researchers. Therefore, it can be assumed that Henning et al. model for accelerated rutting has no effect of camber in it.

### 5.3.4. LWP and RWP stable rut progression rate

It was assumed that the stable rut progression rate of a thin granular pavement is 0.5mm/year and for a thick granular pavement is 0.1mm/year. On rural New Zealand road that carries roughly $10^5$ ESAL per year. Using this information and the difference in LWP and RWP from Equation 13 to 16, Figure 39 can be produced.

### 5.3.5. LWP and RWP accelerated rutting

Using the increased ESAL calculations from Equations 13 to 16 as an input into the accelerated rutting model from Equation 20 it will produce the following Figure 40 and 41.

# 5.4. Results/ Analysis

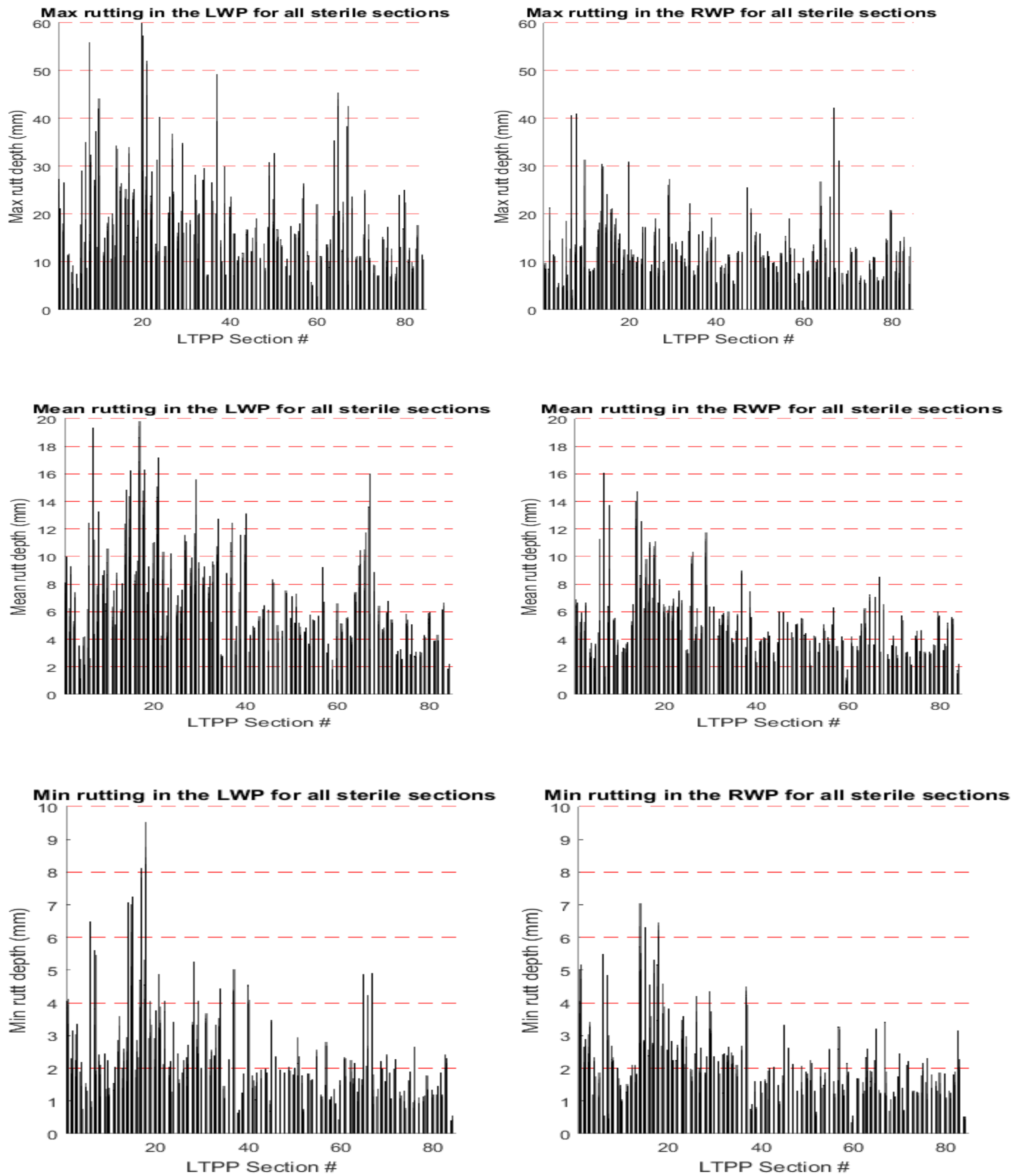



*Figure 38 Showing max, mean and min rut depths for all sterile sections of the New Zealand LTPP.*

Figure 38 shows a direct comparison of max, mean and min of the left and right wheel paths for the sterile LTPP sections.

*Table 15: Percentages exceeding the indicated rut depth (left column) for different distribution descriptors: max, mean and min. This includes the values for all years of the LTPP.*

| Descriptor | Max | | Mean | | Min | |
|---|---|---|---|---|---|---|
| Rut depth(mm) | LWP | RWP | LWP | RWP | LWP | RWP |
| 2.0 | 99.8 | 99.8 | 96.7 | 96.3 | 34.5 | 32.2 |
| 4.0 | 99.3 | 97.7 | 77.2 | 54.3 | 7.9 | 4.9 |
| 6.0 | 95.3 | 86.6 | 46.5 | 22.4 | 2.8 | 0.7 |
| 8.0 | 86.4 | 69.5 | 25.2 | 7.8 | 0.6 | 0.0 |
| 10.0 | 77.1 | 52.1 | 12.6 | 3.3 | 0.0 | 0.0 |
| 12.0 | 64.1 | 34.5 | 6.9 | 1.0 | 0.0 | 0.0 |
| 14.0 | 54.2 | 21.5 | 4.4 | 0.2 | 0.0 | 0.0 |
| 16.0 | 43.7 | 14.5 | 1.5 | 0.1 | 0.0 | 0.0 |
| 18.0 | 33.2 | 9.8 | 0.5 | 0.0 | 0.0 | 0.0 |
| 20.0 | 26.1 | 7.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 25.0 | 13.6 | 2.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| 30.0 | 6.4 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 35.0 | 3.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| 40.0 | 1.6 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| 50.0 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 60.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 15 shows the proportion of sections that exceed trigger values in the leftmost column for specific statistical descriptors. The maximum values are of most interest to us as this is accepted to govern intervention. Table 15 shows that the maximum values in the LWP exceed all RWP values. This is particularly so in the range of rut depth of 10 -20 mm where the difference is roughly 30%. The mean rut depth is also an important factor as this gives us the most general idea of the whole length of sections performance. Results again show that LWP that a higher proportion of sections are exceeding deeper rut depths than the RWP. The last two columns show the minimum rut depths in the left and right wheel paths for all sterile sections. The same difference is present her however not as prevalent.

### 5.4.1. LWP and RWP Stable rut progression model

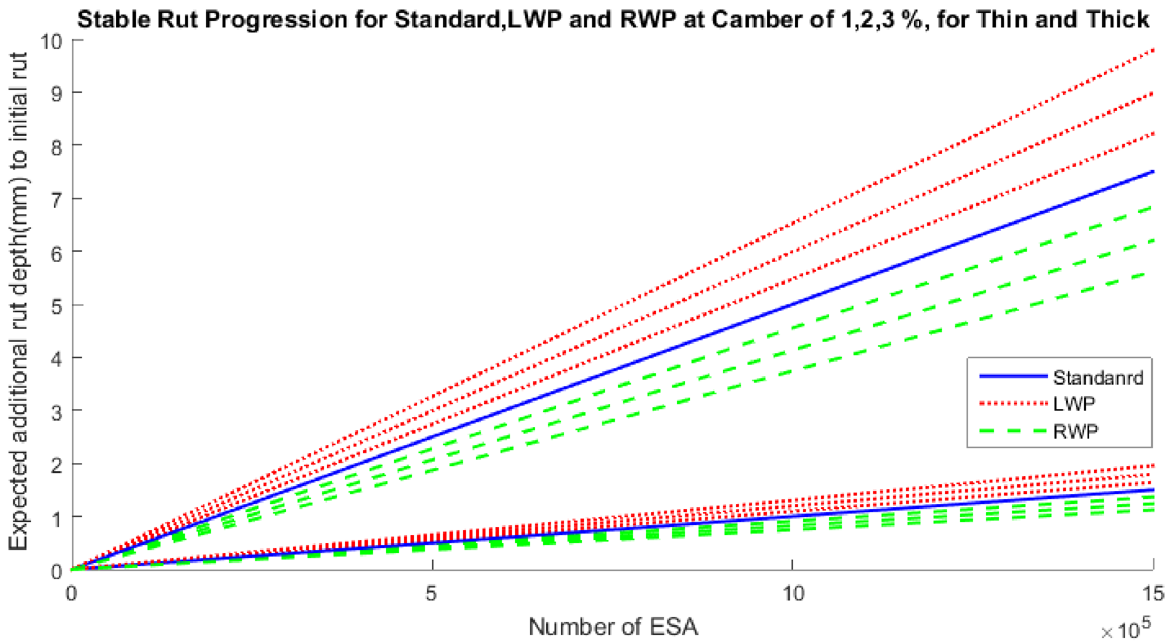



*Figure 39: Illustration the effect of camber on stable rut progression Phase for both thin (top) RPR = 0.5mm/10⁵ESAL and thick (top) RPR = 0.1mm/10⁵ESAL.*

Figure 39 illustrates how camber can have an effect on stable rut progression Phase 2. This figure shows that there is a difference between LWP and RWP stable rut progression. The higher ESAL values expected in the LWP multiplied by the RPR yields deeper ruts more quickly over time and load. The opposite is true for the RWP. It is clear that this effect is more apparent on thin granular pavements with relatively high RPR compared to thicker granular pavements with lower RPR.

## 1.1 LWP and RWP accelerated rutting model

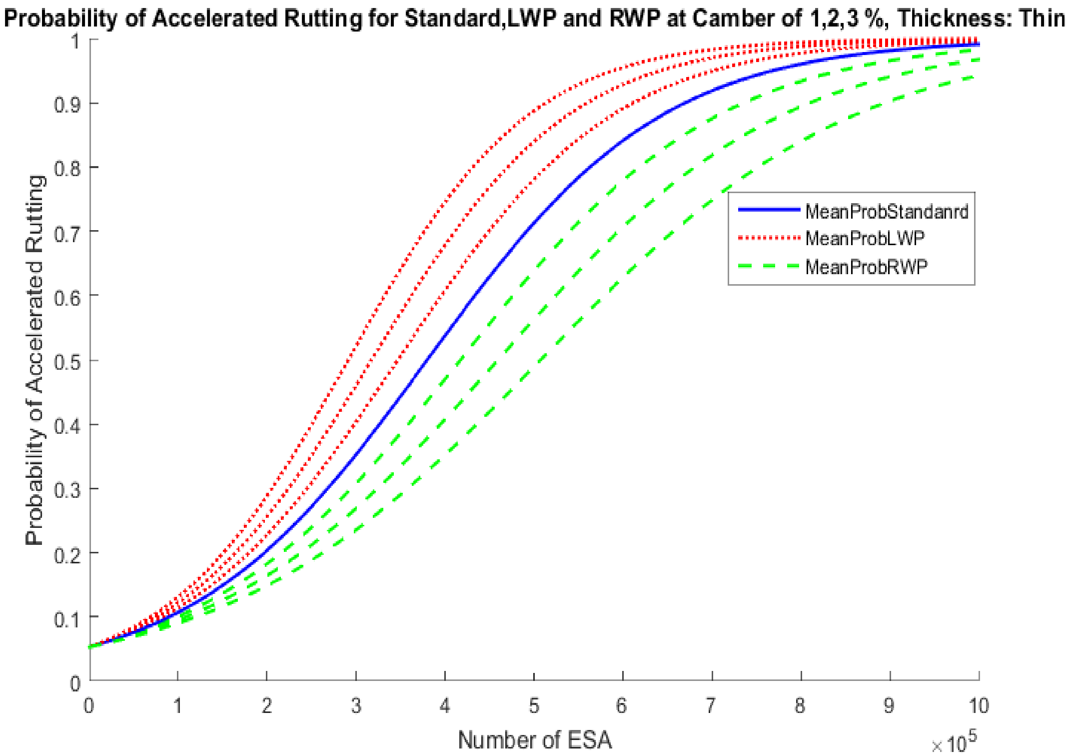



*Figure 40: Illustrates the mean probability of accelerated rutting for standard, LWP, and RWP at camber of 1, 2, and 3 %. Closest red and green lines to the solid blue line represent 1 % camber LWP and RWP respectively. This is for thin granular pavements at SNP of 3.*

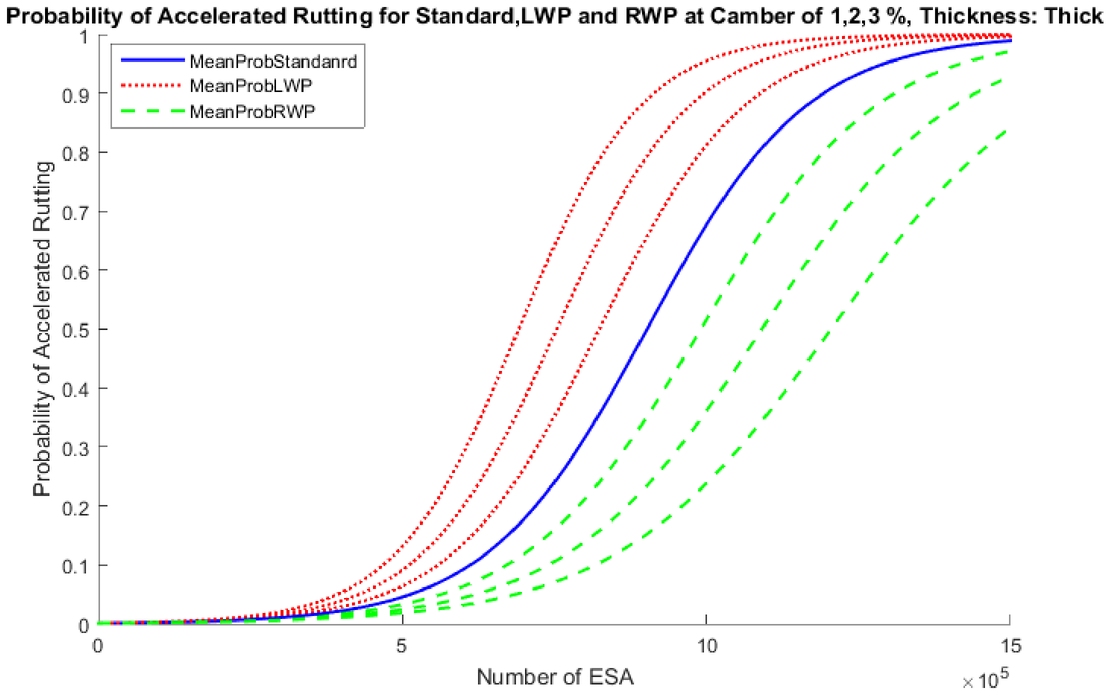



*Figure 41: Illustrates the mean probability of accelerated Rutting for standard, LWP, and RWP at camber of 1, 2, 3 %. Closest red and green lines to the solid blue line represent 1 % camber LWP and RWP respectively. This is for thick granular pavements at SNP of 3.*

From Figures 40 and 41 above it can be noted that the probability of failure in the LWP is greater than the probability of failure in the RWP. As camber increases from 0-3 % this difference in probability increase as shown. As accelerated rutting is occurring more often in the LWP, that maintenance would need to be done more regularly in the LWP than if there was no camber. It is also important to note that as camber increases the likely hood of the RWP experiencing accelerated rutting decreases. This means, in reality, less maintenance would need to be conducted on the inside wheel path. This difference is more pronounced in the thick pavement. The difference in left and right wheel path ESAL due to camber will have a greater effect on large numbers of ESAL experienced by thicker pavements than a smaller number of ESAL experienced by thinner payments.

## 5.5. Discussion

### 5.5.1. Limitations of models

This camber model included the effects of camber on straight rural roads only. The effect of camber on bends, up hills and down hills have not been analysed in this study. The Camber model did not account various heavy vehicle configurations and weights. Only static conditions were taken account of. Camber calculation was a static analysis and did not include the effects of the dynamic behaviour of vehicles geometry and loads. Additionally, no vehicle details have been taken into account like overhanging loads and shock absorbers, which can amplify the camber effect, increasing the load in the LWP. Pavement imperfections like potholes and pothole repairs have not been taken into account either. Effects of limited shoulder support and Environmental factors have also no been taken account off.

This methodology is heavily dependent on the power rule and exponent 4 given by Austroads. Numerous authors reasoned that for thin lightly trafficked granular pavements a fixed power law the EXP value will probably need to be larger than 4. It has been suggested that a value or around 7 is used by various studies (Dawson, 2008; Dorman, 1965; Jameson, 1996). If this is the case the camber effect will be much greater.

Many researchers dismiss the use of SNP in deterioration due to its many limitations and favour the use of FWD. However, for this research, the use of SNP has minimal effect as it was kept constant throughout the investigation.

### 5.5.2. Accelerated rutting stage might not govern the intervention

The models developed by T.F.P Henning et al. was developed from CAPTIF data. Therefore, it is limited to variables in the CAPTIF and may not include variables that occur in the field. Accelerated rutting may not be the driving factor for intervention if Phase 2 the stable rut progression stage reaches the terminal rut before Phase 3 occurs. This is more likely to happen on thicker pavements as high probabilities of accelerated rutting is significantly prolonged compared to that of thinner pavements (Theuns Henning et al., 2009).

## 5.6. Conclusions

The LTPP data from New Zealand shows that there is a significant difference between rutting of the inside (RWP) and outside (LWP) wheel paths. In the LWP, rutting is significantly deeper than in the RWP. As rutting is related to loading, it stands to reason that camber is primarily responsible for the found difference in rutting.

By adopting the effect of loading, the individual wheel path rutting has been predicted using models developed in New Zealand. Results from this model show that as camber becomes steeper, it significantly increases the probability of accelerated rutting in the outside wheel paths while it decreases for the inside wheel paths. This will result in the outside wheel path failing sooner and governing maintenance procedures over time. This result forces a re-think of anecdotal homogenous pavement assumptions and methods to extend pavement life.

# Chapter 6 Recommendations

# Purpose of this chapter

Many of the recommendations developed from this research have already been discussed in previous chapters. This chapter is intended to pull the key recommendations together into a combined and concise message.

## 6.1. The need to change homogeneous design assumptions

The results from the SBMDM and the two following case studies (site specific investigation) chapter 4 and (network investigation) chapter 5, argue that there is a need to fundamentally change the design assumptions for chip seal roads.

This research has demonstrated that there is a difference in wheel path loading due to camber. It has also shown a significant difference in rutting of the inside wheel path compared to outside wheel path. Therefore, this research argues that the homogeneous pavement design method should change to match the difference in loading and deterioration shown by these findings. If this is done, pavement life would likely be extended and provide better value for the public with respect to PMS.

Limited methods as of yet have been developed to confront this problem. It is recommended that practitioners and researchers conduct further research in this area. Like with all methods to extend pavement life it should be done within the pavement management context and aim to provide value to the end user.

## 6.2. This tool with relation to maintenance data

The SBMDM is not indented for maintenance use in its current state. However, it is believed that with further research the SBMDM could be used to gain valuable information regarding different maintenance procedures and operations.

This tool is not recommended for carrying out maintenance procedures. This tool was designed to analyse pavement data more effectively and to allow practitioners to identify sections of pavement of interest. In a maintenance scenario, engineers are only interested in one specific pavement section and not generally interested in the comparison of multiple sections. In a maintenance scenario, a Vector Approach is more appropriate as suggested by D. Jeong, ISU.

## 6.3. Development of graphical user interface

Although SBMDM has shown many advantages, the disadvantages must also be acknowledged. To use the SBMDM in its current state required an in-depth understanding of computer science concepts as well as pavement engineering. This makes the tool primarily suited to researchers. It is recommended that further development is conducted to produce an easy to understand user interface.

## 6.4. Data quality

A large investment must be made if we want to use the RAMM database as a research tool. Currently, all conclusion based on RAMM data can be undermined through the argument of data quality. It is true however small investigations with validated data can be conducted, but this is an extremely time-consuming process. Researchers with limited budgets do not have the required resources to validate data from RAMM. So instead must focus on more credible databases such as the LTPP and industry data.

A major shortcoming of the LTPP data is that some sections were not documented well before the LTPP's inception. This results in incomplete data sets with regards to what has been built. Test pits were dug to establish the makeup of sections however some results from these test pits were inconclusive.

Within the current version of the LTPP database GPS data was extremely difficult to interpret as multiple standards were used. It is recommended that this is improved as this would make the current data much more easily interfaced with other geospatial databases.

## 6.5. Further research

This tool has largely focused on the performance indicator - 'rutting.'  This was a conscious decision made because of expert's recommendation. However, there is still much to be done with regards to the other performance indicators in the SBMDM. It is recommended that further investigation is conducted with regards to IRI and texture in particular. It is also recommended that other data sources be added to the SBMDM

This research has largely focused on sterile pavement sections. This decision was made to limit the variability introduced by maintenance during the case studies presented. It is recommended that this tool be further developed to take advantage of maintenance data as well as costing data. These performance indicators could possibly be combined to allow comparisons of different pavement strategies.

Finally, it is recommended that further research is conducted in the areas of limited shoulder size and drainage effect on key performance indicators discussed.

# Chapter 7 Conclusions

## 7.1. Conclusions

A need has been identified by NZTA to develop tools that will extract more information out of the ageing pavement databases. A new tool has been demonstrated to help understand pavement condition data from a holistic point of view called the SBMDM. This tool incorporates multi-dimensional databases, Fuzzy logic, and the Delphi method. Fuzzy membership sets are established through performance data and not expert opinion. This tool is able to rank pavement sections based on a range of factors that are most appropriate to the user. This can inform engineers which pavement is performing well to repeat pavement success. The SBMDM was demonstrated through the use of a case study where three performance indicators were analysed from the New Zealand LTPP. This SBMDM was shown to be able to rank pavement with expert opinion.

While investigating data quality, a need was identified to ensure LTPP data was being collected in the right location with respect to the wheel paths. This research has demonstrated a new methodology that can find the lateral wheel path distribution on roadways in New Zealand. This methodology has been executed on several rural sites around the Canterbury Region. The results show that the method employed by NZTA to find the lateral position to record condition data is valid on a straight section of road. The wheel path spacing and width has been analysed and presented for several sites. Using these results contractors are better equipped to calibrate the variable bitumen spray bar thereby prolonging pavement life. Results presented, show that the load concentration in the wheel path is much narrower than original anecdotal assumptions suggests. This impacts pavement design assumptions that presume far more vehicle wander. Preliminary work has been conducted on curved sections. However, more work is needed to understand the lateral distribution of vehicles on curved sections due to the many complexities.

Utilising the SBMDM an investigation into local pavement sections was conducted. The SBMDM identified two sections in the Canterbury region of interest. A detailed assessment of two sections of road in New Zealand where pronounced differences between rutting depths in the left and right wheel paths were found. The rutting on the right wheel paths was consistently shallower than on the left wheel path. A free body diagram illustrated that camber could give rise to a shift in loading from the right to left wheel. This shift in loading can cause a significant change in ESAL calculations.

Following this, the SBMDM was further used to conduct research at a network level. The difference in rutting was investigated at a network level. It showed that this difference in rutting was not a localized issue. As rutting is related to loading, it stands to reason that camber is primarily responsible for the found difference in rutting. By adopting the effect of loading, the individual wheel path rutting has been predicted using models developed in New Zealand. Results from this model show that as camber becomes steeper, the probability of accelerated significantly increases in the outside wheel path while it decreases for the inside wheel path. This will result in the outside wheel path failing sooner and governing maintenance procedures over time. This result forces a re-think of anecdotal homogenous pavement assumptions and methods to extend pavement life.

# Chapter 8 References

## 8.1. References

Abtahia, S. M., Sheikhzadehb, M., & Hejazib, S. M. (2009). Fiber-reinforced asphalt-concrete – A review. *Construction and Building Materials, 24*(6), 871-877.

Adlinge, S. S., & Gupta, A. (2013). Pavement Deterioration and its causes. *International Journal of Innovative Research and Development, 2*(4), 437-450.

Aksnes, J., Hoff, I., & Mork, H. (2002). *Measurement of edge effects on pavements with thin asphalt surfacing.* Paper presented at the Ninth International Conference on Asphalt Pavements, Copenhagen 2002.

Alabaster, D. J., Fussell, A. W., & Land Transport, N. (2006). *Fatigue design criteria for low noise surfaces on New Zealand roads*: Land Transport New Zealand.

Arnold, G., & Land Transport, N. (2005). *Effect on Pavement Wear of Increased Mass Limits for Heavy Vehicles: Concluding Report*: Land Transport New Zealand.

Arnold, G., Werkmeister, S., & Alabaster, D. (2008). *Performance tests for road aggregates and alternative materials*. Retrieved from Land Transport NZ research report 335:

Arnold, G. K. (2004). *Rutting of granular pavements(Thesis).* University of Nottingham.

Austroads. (1992). A Guide to the Structural Design of Road Pavements. *Austroads Publication No. APGP17/04. Austroads, Sydney*.

Austroads. (2004). 2004a Pavement Design-A Guide to the Structural Design of Road Pavements. Revision 2. Sydney, NSW , Australia: AUSTROADS.

Austroads. (2007). *Guide to Pavement Technology Part 4B: Asphalt* Australia. Austroads. Sydney.NSW. Australia.

Bertelsen, S. (2003, July). Construction as a complex system. In *proceedings of IGLC* (Vol. 11, pp. 143-168).

Blab, R., & Litzka, J. (1995). *Measurements of the lateral distribution of heavy vehicles and its effects on the design of road pavements.* Paper presented at the Proceedings of the International Symposium on Heavy Vehicle Weights and Dimensions, Road Transport Technology, University of Michigan.

Brown, D. (2005). *Measuring pavement condition data for the establishment of a long-term pavement performance study on New Zealand roads.* Paper presented at the International surface friction conference: roads and runways: improving safety through assessment and design. Christchurch, New Zealand.

Buiter, R., Cortenraad, W., Van Eck, A., & Van Rij, H. (1989). Effects of transverse distribution of heavy vehicles on thickness design of full-depth asphalt pavements. *Transportation research record*(1227).

Carey, W. N., & Irick, P. E. (1960). The Pavement Serviceability Performance Concept. *Highway Research Board, Record 250*.

Cenek, P., Henderson, R., Forbes, M., Davies, R., & Tait, A. (2014). The relationship between crash rates and rutting January 2014.NZTA.

Cenek, P., Henderson, R., McIver, I., & Patrick, J. (2012). *Modelling of extreme traffic loading effects October 2012*. Retrieved from NZ Transport Agency research report 499:

CEOS-Industrials. (2005). *TIRTL Installation Manual*. CEOS-Industrials

Cheng, H.-D., & Miyojim, M. (1998). Automatic pavement distress detection system. *Information Sciences, 108*(1-4), 219-240.

Colliat, G. (1996). OLAP, relational, and multidimensional database systems. *ACM SIGMOD Record, 25*(3), 64-69.

Collins, I., & Boulbibane, M. (2000). Geomechanical analysis of unbound pavements based on shakedown theory. *Journal of Geotechnical and Geoenvironmental Engineering, 126*(1), 50-59.

Dalkey, N., & Helmer, O. (1963). An experimental application of the Delphi method to the use of experts. *Management Science, 9*(3), 458-467.

Dawson, A. (2008). Rut accumulation and power-law models for low-volume pavements under mixed traffic. *Transportation Research Record: Journal of the Transportation Research Board*(2068), 78-86.

Dock, F., Bochner, B., & Greenberg, E. (2004). Multidimensional framework for context-based design of major urban thoroughfares. *Transportation Research Record: Journal of the Transportation Research Board*(1890), 81-87.

Dorman, G. (1965). Design curves for flexible pavements based on layered system theory. *Highway Research Record, 1*(71), 69-84.

Feighan, K. J., Shahin, M. Y., & Sinha, K. C. (1987). *A dynamic programming approach to optimization for pavement management systems.* Paper presented at the 2nd North American Pavement Management Conference.

Fwa, T., Tan, S., & Zhu, L. (2004). Rutting Prediction of Asphalt Pavement Layer Using C-ϕ Model. *Journal of transportation engineering, 130*(5), 675-683.

Geiger, D., Wells, P., Bugas-Schramm, P., Love, L., McNeil, S., Merida, D., . . . Velasquez, L. ( 2005). *Transportation Asset Management In Australia, Canada, England, and New Zealand*. Retrieved from American Trade Initiatives P.O. Box 8228 Alexandria, VA 22306-8228:

Gransberg, D., & Pidwerbesky, B. (2007). Strip sealing and ultra-high-pressure water cutting technique for restoring skid resistance on low-volume roads: Life-cycle cost comparison. *Transportation Research Record: Journal of the Transportation Research Board*(1989), 234-239.

Gransberg, D., Pidwerbesky, B., & James, D. M. (2005). *Analysis of New Zealand chip seal design and construction practices.* Paper presented at the Transportation Research Circular No. E-C078: Roadway Pavement Preservation 2005: Papers from the First National Conference on Pavement Preservation, Kansas City, Missouri October 31–November 1.

Gransberg, D., & James, D. M. (2005). *Chip seal best practices NCHRP* (Vol. 342). Washington, D.C: Transportation Research Board.

Gribble, M., Patrick, J., & Land Transport, N. (2008). *Adaptation of the AUSTROADS pavement design guide for New Zealand conditions*. New Zealand Land Transport NZ research report 305.

Gunaratne, M., Chameau, J.-L., & Altschaeffl, A. (1984). *Introduction to Fuzzy Sets in Pavement Evaluation (Abridgment). Transportation Research Record*.

Gunaratne, M., Chameaut, J., & Altschaefflf, A. (1985). Fuzzy multi-attribute decision making in pavement management. *Civil Engineering Systems, 2*(3), 166-170.

Haas, R. H. (1994). WR, and Zaniewski, J., 1994, Modern Pavement Management: Krieger Publishing Company, Florida, USA.

Henning, T.F.P., Costello, S., Dunn, R., Parkman, C., & Hart, G. (2004). The establishment of a long-term pavement performance study on the New Zealand state highway network. *Road and Transport Research, 13*(2).

Henning, T.F.P., Dunn, R., Costello, S., & Parkman, C. (2009). A new approach for modelling rutting on the New Zealand State Highways. *Transport Research: A Journal of Australian and New Zealand Research and Practice*.

Henning, T.F.P., & Roux, D. (2008). *Pavement deterioration models for asphalt-surfaced pavements in New Zealand*. Wellington, New Zealand NZ Transport Agency research report 367.

Henning, T.F.P., Costello, S., & Watson, T. (2006). *A review of the HDM/dTIMS pavement models based on calibration site data*. Retrieved from Wellington, New Zealand

Henning, T.F.P., Costello, S., & Watson, T. (2006). *A review of the HDM/dTIMS pavement models based on calibration site data*: Land Transport NZ.

Henning, T.F.P., Dunn, R., Costello, S., Hart, G., Parkman, C., & Burgess, G. (2004). *Long-term pavement performance (LTPP) studies in New Zealand: lessons, the challenges and the way ahead.* Paper presented at the 6th International Conference on Managing Pavements: The Lessons, The Challenges, The Way Ahead, Brisbane.

Henning, T.F.P. (2008). *The Development of Pavement Deterioration Models on the State Highway Network of New Zealand.* (PhD Thisis), University of Auckland, Auckland.

Henning, T.F.P., Costello, S. B., & Watson, T. (2006). *A review of the HDM/dTIMS pavement models based on calibration site data*. New Zealand: Land Transport New Zealand. Wellington.

Henning, T.F.P., Costello, S., Dunn, R., Parkman, C.C. and Hart, G. (2004) The Establishment of A Long-Term Pavement Performance Study on The New

Zealand State Highway Network. Accepted for publication in the ARRB Journal.

Henning, T.F.P. and Roux, D.C. 2008. Pavement deterioration models for asphalt-surfaced pavements in New Zealand. NZ Transport Agency Research Report 367. Wellington, New Zealand: NZ Transport Agency.

Hicks, R., Moulthrop, J., & Daleiden, J. (1999). Selecting a preventive maintenance treatment for flexible pavements. *Transportation Research Record: Journal of the Transportation Research Board*(1680), 1-12.

Hudson, W. R., McCullough, B. F., Scrivner, F., & Brown, J. L. (1970). A Systems Approach Applied to Pavement Design and Research. *Transportation Research Record: Journal of the Transportation Research Board*

Islam, M., Tarefder, R., & Syed, I. (2014). Measurements of lateral distribution of vehicle wheels and its effect on fatigue life of asphalt concrete. *Sustainability, Eco-efficiency, and Conservation in Transportation Infrastructure Asset Management*, 379.

Jameson, G. (1996). Origins of AUSTROADS design procedures for granular pavements, Report ARR 292. *September, ARRB Transport Research Ltd., Vermont South, Australia*.

Kasahara, A. (1982). *Wheel path distribution of vehicles on the highway.* Paper presented at the Proceedings of an International Symposium on Bearing Capacity of Roads and Airfields, Volume 1, Trondheim, held June 23-25, 1982.

Khurshid, M. B., Irfan, M., Ahmed, A., & Labi, S. (2014). Multidimensional benefit–cost evaluation of asphaltic concrete overlays of rigid pavements. *Structure and Infrastructure Engineering, 10*(6), 792-810.

Kodippily, S., Henning, T. F. P., & Ingham, J. M. (2012). Detecting flushing of thin sprayed seal pavements using pavement management data. Department of Civil and Environmental Engineering Faculty of Engineering The University of Auckland.

Kucukvar, M., Gumus, S., Egilmez, G., & Tatari, O. (2014). Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision-making method. *Automation in construction, 40*, 33-43.

Kuhn, K. D. (2011). Pavement network maintenance optimization considering multidimensional condition data. *Journal of Infrastructure Systems, 18*(4), 270-277.

La Bar, J., Rizzutto, S. J., Johannes, P. T., & Bahia, H. U. (2015). Use of a Variable Rate Spray Bar to Minimize Wheel Path Bleeding for Asphalt-Rubber Chip Seal Applications. *Journal of materials in civil engineering, 27*(3), 4014121. doi:10.1061/(ASCE)MT.1943-5533.0001035

Ladyman, J., Lambert, J., & Wiesner, K. (2012). *What is a complex system* University of Bristol U.K. Retrieved from http://philsci-archive.pitt.edu/9044/4/LLWultimate.pdf (accessed 2015)

Laker, K. (2006). *Benefits of a Multi-Dimensional Model* Retrieved from Oracle Corporation.Retrieved from : http://www.oracle.com/technetwork/developertools/warehouse/benefits.pdf (accessd 2016)

Larson, J., Lossau, K., & Walsh, D. (2011). Correlation Using Pair-wise Combinations of Multiple Data Sources and Dimensions at Ultra-Large Scales.Github

Lay, M. (1998). *Handbook of Road Technology. Volume 2: Traffic and Transport*: Gordon and Breach Science Publishers, London (England).

Leslie, A. (2014). [Discussion of Pavement technology with a national pavements Engineer at Fulton Hogan].

Linstone, H. A., & Turoff, M. (1975). *The Delphi method: Techniques and applications* (Vol. 29): Addison-Wesley Reading, MA.

Luk, J. (2006). *Automatic vehicle classification by vehicle length*. Austroads. Australia

Luo, W., & Wang, K. C. (2013). Wheel path wandering based on field data *Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements* (pp. 506-515).

Ma, Z., Shao, C., Ma, S., & Ye, Z. (2011). Constructing road safety performance indicators using fuzzy Delphi method and grey Delphi method. *Expert Systems with Applications, 38*(3), 1509-1514.

Mamlouk, M. (2014). *Sustainability and Pavement Design Implementation.* Paper presented at the University of Canterbury New Zealand, New Zeland

Martin, T. (2003). Pavement performance prediction deterioration model development: data review and calibration of HDM-4 road deterioration models. *AUSTROADS Project No: BS. AN, 552*.

MathWorksInc. (2017). Matlab Practice Support , R2017a Documentation Retrieved from https://au.mathworks.com/help/stats/prctile.html (Accessed 2017)

Matlab. (2014). Multidimensional Arrays. Retrieved from http://au.mathworks.com/help/matlab/math/multidimensional-arrays.html (Accessed 2016)

McComb, R. A. (1988). AN OVERVIEW OF THE STRATEGIC HIGHWAY RESEARCH PROGRAM. In International Symposium on Heavy Vehicle Weights and DimensionsTransportation Association of Canada.

Milliken, P., & de Pont, J. (2004). *The effect of cross-sectional geometry on heavy vehicle performance and safety*. Transfund New Zealand Research, Report 263, 2004. Wellington, New Zealand

Minnesota-DOT. (2007). *Introduction to the International Roughness Index.* Paper presented at the Bituminous Smoothness Training Workshop, Minnesota Department of transportation

Mitchell, M., & Newman, M. (2002). Complex Systems Theory and Evolution. Encyclopedia of Evolution 1-5.

Moazami, D., Behbahani, H., & Muniandy, R. (2011). Pavement rehabilitation and maintenance prioritization of urban roads using fuzzy logic. *Expert Systems with Applications, 38*(10), 12869-12879.

Mueller, T., De Pont, J., & Baas, P. (1999). Heavy vehicle stability versus crash rates. *A report prepared for The Land Transport Safety Authority*.

NAMS. (2015). National Asset Management Steering Committee Retrieved from http://www.nams.org.nz/pages/16/about-us.htm (Accessed 2016)

NPTEL. (2007). Factors affecting pavement design. Retrieved from http://nptel.ac.in/courses/105101087/downloads/Lec-20.pdf (Accessed 2016)

NZTA. (2005). *Chipsealing in New Zealand. Transit NZ . Wellington.* New Zealand

NZTA. (2011). *State Highway Asset Management Plan 2012–2015*. NZTA*. Wellington.* New Zealand

NZTA. (2014). *NZTA annual report (end 30 June 2014)*. Retrieved from http://www.nzta.govt.nz/resources/annual-report-nzta/2013-14/2013-14-annual-report.html(Accessed 2016)

NZTA. (2015). Heavy rigid motor vehicle definitions and specifications. Retrieved from http://www.nzta.govt.nz/resources/roadcode/heavy-vehicle-road-code/information-for-heavy-vehicle-drivers/heavy-rigid-vehicle-definitions-and-specifications/(Accessed 2016)

NZTA. (2015). *Request for Proposal: Asset Management Research Topics 2*. NZTA. Wellington. New Zealand.

NZTA. (2016). Active research projects. Retrieved from https://www.nzta.govt.nz/planning-and-investment/our-investments/research/active-research-projects/ (Accessed 2016)

Ong, G. P., Pasindu, H. R., & Fwa, T. F. (2012). Critical Rut Depth for Pavement Maintenance Based on Vehicle Skidding and Hydroplaning Consideration. *Journal of transportation engineering, 138*(4), 423-429. doi:10.1061/(ASCE)TE.1943-5436.0000336

Oracle. (2006). *Benefits of a Muti-Dimensional Model* Retrieved from http://www.oracle.com/technetwork/developer-tools/warehouse/benefits.pdf (Accessed 2016)

Oxford Dictionary. (2014). Oxford Dictionary Retrieved from http://www.oxforddictionaries.com/definition/english/stochastic?q=STOCHASTIC (Accessed 2016)

Pan, N.F. (2008). Fuzzy AHP approach for selecting the suitable bridge construction method. *Automation in construction, 17*(8), 958-965.

Park, J., & Cai, H. (2017). WBS-based dynamic multi-dimensional BIM database for total construction as-built documentation. *Automation in construction, 77*, 15-23.

Pasupathy, R., Ivan, J. N., & Ossenbruggen, P. J. (2000). *Single and multi-vehicle crash prediction models for two-lane roadways* (No. NEUTC UCNR9-8,). New England University Transportation Center [Massachusetts Institute of Technology].

Pavement-Interactive. (2011). Bituminous Surface Treatments Retrieved from http://www.pavementinteractive.org/2011/07/19/bituminous-surface-treatments/ (Accessed 2016)

PavementInteractive. (2007). Equivalent Single Axle Load. Retrieved from http://wiki.pavementinteractive.org/index.php?title=ESAL#Generalized_Fourth_Power_Law (Accessed 2016)

Pidwerbesky, B. (2014). *A holistic approach to flexible pavement design improves performance.* Paper presented at the ARRB Conference, 26th, 2014, Sydney, New South Wales, Australia.

Pidwerbesky, B. (2015, 20 March 2015 1pm ). [Personal communication ].

Pidwerbesky, B., & Waters, J. (2007). Sustainable innovative surfacing treatments for low-volume roads. *Transportation Research Record: Journal of the Transportation Research Board*(1989), 173-180.

Pidwerbesky, B. (1995). Accelerated dynamic loading of flexible pavements at the Canterbury accelerated pavement testing indoor facility. *Transportation research record*(1482), 79-86.

Porter, R., Donnell, E., & Mahoney, K. (2004). Evaluation of effects of centerline rumble strips on lateral vehicle placement and speed. *Transportation Research Record: Journal of the Transportation Research Board*(1862), 10-16.

Ramadhan, R. H., Al-Abdul Wahhab, H. I., & Duffuaa, S. O. (1999). The use of an analytical hierarchy process in pavement maintenance priority ranking. *Journal of Quality in Maintenance Engineering, 5*(1), 25-39.

RAMM. (2014). Road Assessment and Maintenance Management. Retrieved from http://www.ramm.com/ (Accessed 2016)

Robinson, R., Danielson, U., & Snaith, M. (1998). *Road Maintenance Management-Concepts and Systems*. Basingstoke and London: Macmillan Press.

Rowe, G., & Wright, G. (2001). Expert opinions in forecasting: the role of the Delphi technique. In Principles of forecasting(pp. 125-144). Springer, Boston, MA.

Saleh, M. (2013). *ENCN 415 Course material, Pavement Engineering.* University of Canterbury , New Zealand

Saleh, M. F., & Patrick, J. (2006). Investigation of the effect of shoulder properties, axle load, and tyre pressure on edge failure of thin surfaced granular pavements. *Journal of ARRB Transport Research, 15*(3), 19-35.

Sanford-Bernhardt, K. L., & McNeil, S. (2004). *Modeling interdependencies in infrastructure management using complex systems.* Paper presented at the Applications of Advanced Technologies in Transportation Engineering. Eighth International Conference.

SaRS. (2004). *Applied R&M Manual for Defence Systems* Retrieved from U.K. : http://www.sars.org.uk/old-site-archive/BOK/Applied%20R&M%20Manual%20for%20Defence%20Systems%20(GR-77)/p4c04.pdf (Accessed 2016)

Schlotjes, M. R., Henning, T. F. P., & Burrow, M. P. N. (2012). *Improved network understanding - a diagnostic approach to the risk of pavement failure*. Paper presented at the 8th International Conference on Managing Pavement Assets.

Senadheera, S. P., & Khan, J. R. (2001). Standardized Seal Coat Terminology Pamphlet. TxDOT Research Implementation Study, (5-1787).

Shahin, M. Y., & Kohn, S. D. (1979). Development of a Pavement Condition Rating Procedure for Roads, Streets, and Parking Lots. Volume I. Conditions Rating Procedure (No. CERL-TR-M-268-VOL-1). CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAIGN IL.

Sivilevičius, H., & Vansauskas, V. (2013). Research and evaluation of ruts in the asphalt pavement on Lithuanian highways. *Journal of Civil Engineering and Management, 19*(5), 609-621.

Sprayed Sealing Guide. (2004). *Sprayed Sealing Guide. Austroads.* Sydney. Australia

Standards New Zealand & Standards Australia. (2009). AS/NZSISO31000 Risk management – Principles and guidelines. Joint Australian New Zeeland International standard. Australia , New Zealand

Stevens, D., Salt, G., Henning, T. F. P., & Roux, D. C. (2009). *Pavement Performance Prediction: A Comprehensive New Approach to Defining Structural Capacity (SNP).* Paper presented at the TRANSIT NZIHT 10th ANNUAL CONFERENCE, Rotorua.

Sun, L., & Gu, W. (2010). Pavement condition assessment using fuzzy logic theory and analytic hierarchy process. *Journal of transportation engineering, 137*(9), 648-655.

Tarefder, R., Zaman, M., & Hobson, K. (2003). A laboratory and statistical evaluation of factors affecting rutting. *International Journal of Pavement Engineering, 4*(1), 59-68.

Taylor, W., Abu-Lebdeh, G., & Rai, S. (2005). Effect of continuous shoulder rumble strips and pavement marking on lateral placement of vehicles. *Transportation Research Record: Journal of the Transportation Research Board*(1911), 105-112.

The Contractor. (2012). Flexible Pavement Composition and Structure Retrieved from http://theconstructor.org/transportation/flexible-pavement-composition-and-structure/5499/ (Accessed 2016)

Timm, D. H., & Priest, A. L. (2005). *Wheel Wander at the NCAT Test Track*. Report No 05- 02, National Center for Asphalt Technology, Auburn University, 2005.

Transit-New-Zealand. (2007). New Zealand Supplement to the Document, Pavement Design–A Guide to the Structural Design of Road Pavements (AUSTROADS 2004). *Wellington, New Zealand*.

Tutumluer, E., & Pan, T. (2008). Aggregate morphology affecting strength and permanent deformation behavior of unbound aggregate materials. *Journal of materials in civil engineering, 20*(9), 617-627.

van der Walt, J., Scheepbouwer, E., & Tighe, S. (2016). Differential rutting in Canterbury New Zealand, and its relation to road camber. *International Journal of Pavement Engineering*, 1-7.

Velasquez, M., & Hester, P. T. (2013). An analysis of multi-criteria decision-making methods. *International Journal of Operations Research, 10*(2), 56-66.

Wade, M., Desombre, R., & Peshkin, D. (2001). *High Volume/ High-Speed Asphalt Roadway Preventive Maintenance Surface Treatment.* South Dakota Department of Transportation, Report No. SD99-09, 2001

Wang, D., Lin, X., & Zhang, Y. (2011). Fuzzy logic control for a parallel hybrid hydraulic excavator using genetic algorithm. *Automation in construction, 20*(5), 581-587.

Waters, J. (2014). Personal communication. [Discussion on pavement construction techniques ].

Wind, Y., & Saaty, T. L. (1980). Marketing applications of the analytic hierarchy process. *Management Science, 26*(7), 641-658.

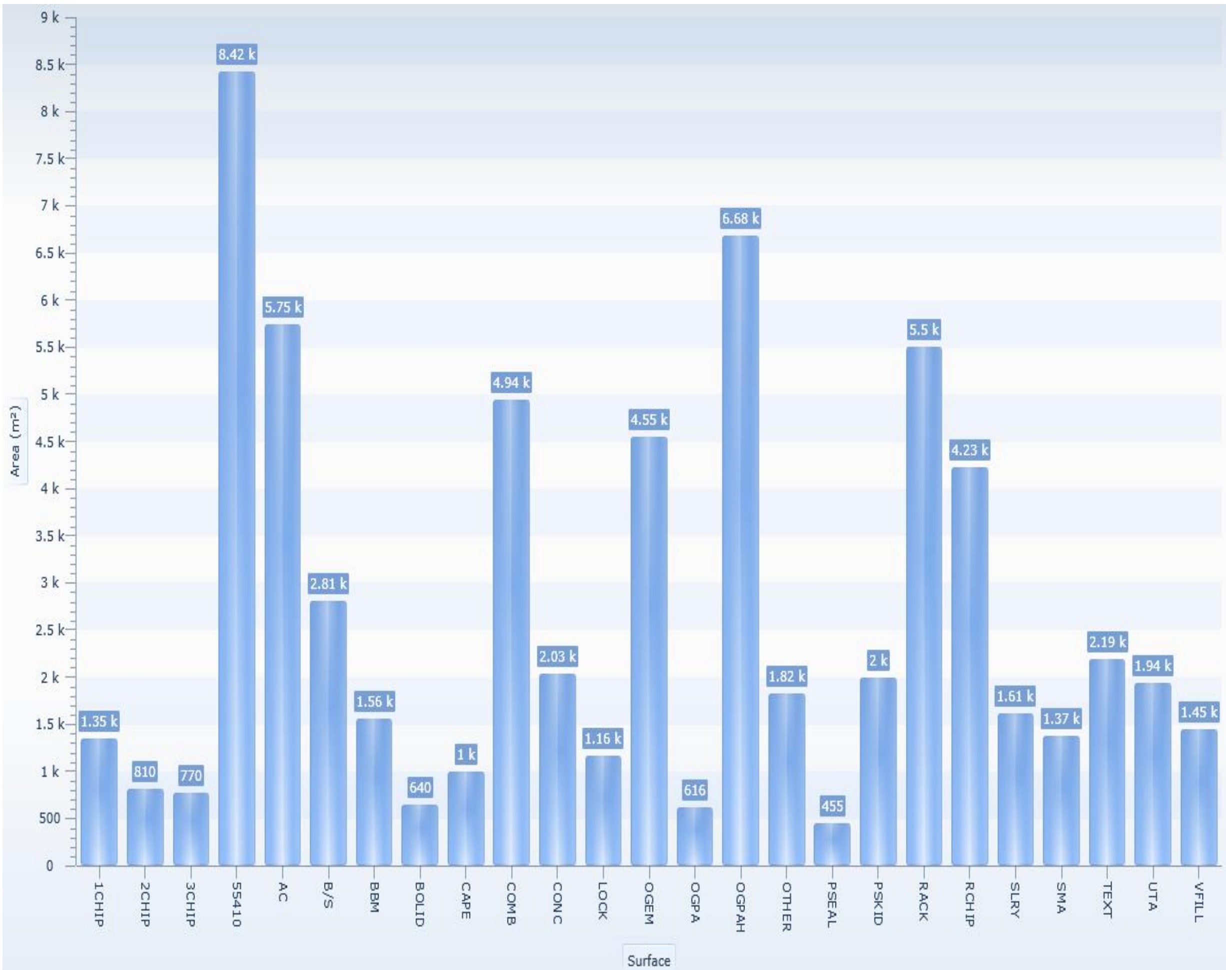
Winkler, C. B., & Ervin, R. (2000). *Rollover of heavy commercial vehicles*. University of Michigan, USA: Society of Automotive Engineers.

Zaghloul, S., & Holland, T. (2008). Comparative analysis of long-term field performance of recycled asphalt in California environmental zones. *Transportation Research Record: Journal of the Transportation Research Board*(2084), 83-99.

**Referencing Style: APA 6th ed. University of Canterbury**

# Chapter 9 Appendix

### 9.1.1. Appendix A: **Distribution of technologies used in New Zealand, 2016 (RAMM database)**




| Mat... | Description |
|---|---|
| AC | Asphaltic concrete |
| BOLID | BOLIDT Polyurethane Mix |
| B/S | Bicouche/Sandwich |
| BBM | Bitumen Bound Macadam |
| CONC | Concrete |
| INBLK | Interlocking concrete blocks |
| LOCK | Locking Coat Seal |
| METAL | Metal running course |
| OGPA | Open Graded Porous Asphalt |
| OGEM | Open graded emulsion mix |
| OTHER | Other material type |
| PSKID | Premium skid surface PSV >7 |
| PSEAL | Prime and seal |
| RACK | Racked in Seal |
| RCHIP | Red Chip Seal (McCullum) |
| 1CHIP | Single Coat Seal |
| SLRY | Slurry Seal |
| SMA | Stone Mastic Asphalt |
| TEXT | Texturising Seal |
| 2CHIP | Two Coat Seal |
| VFILL | Void fill seal |

## 9.1.2. Appendix B: Maintenance procedure for LTPP sites(NZTA, 2002)

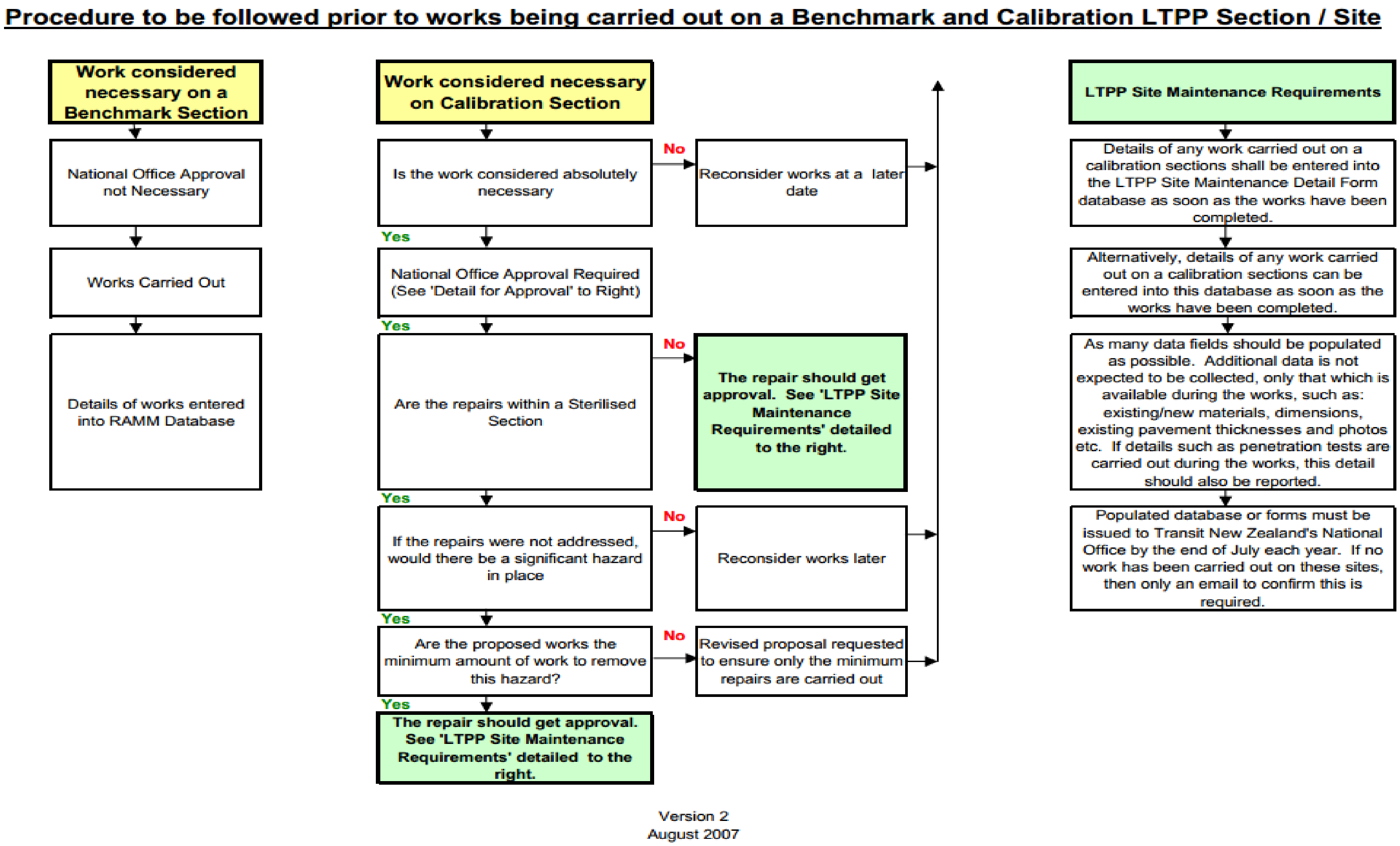
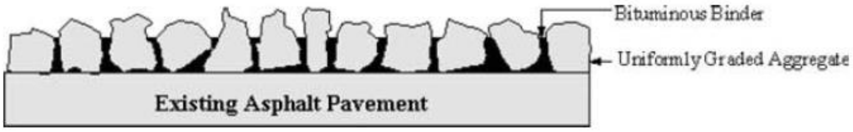
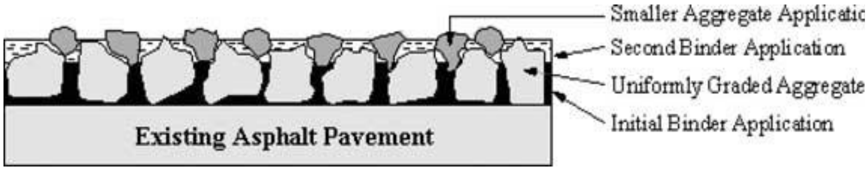
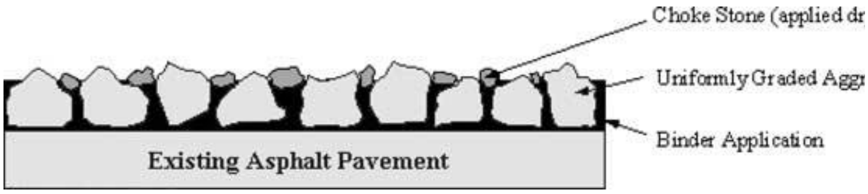
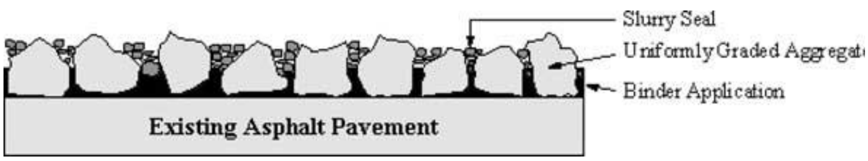
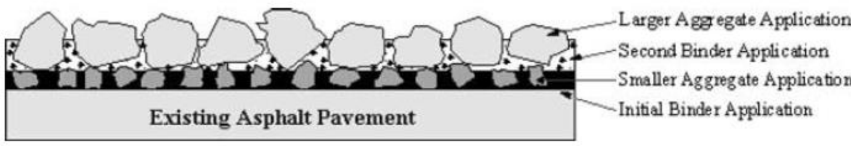
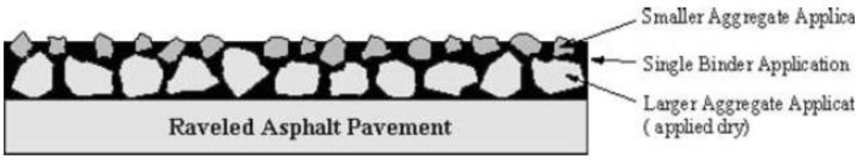


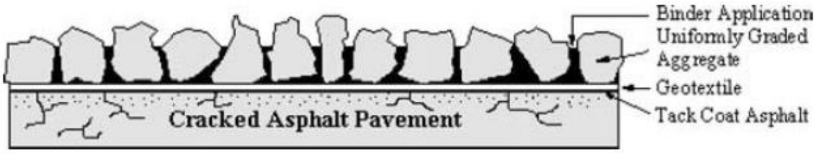
*Table B : Showing the commonly used chip seal types used in New Zealand and internationally (NCHRP Synthesis 342 2005; Sprayed Sealing Guide, 2004)*

| Chip Seal types | General Cross-section of Particular Chip Seal Type |
|---|---|
| **A single chip** is the most common and is selected for a situation where no special concerns warrant the use of another method. Cheapest method. |   |
| **Double chip** has less road noise, provide additional waterproofing and is more robust compared to single chip. It is in a high-stress environment such as steep gradients. |   |
| **Racked in seal** have small particles called choke stones to stop the uniformly graded aggregates from overturning. This type of seal is commonly used in areas where traffic is turning. |   |
| **Cape seal** is a single chip seal followed by a slurry. Cape seals are extremely robust and provide shear resistance comparable to that of asphalt. |   |
| **Inverted Seal** is commonly used to repair a surface that was previously prone to bleeding. They are also used for the restoration of surfaces with variation in transverse surface texture |   |

**Sandwich seal** is used where ravelling has been a major issue.




**The geotextile reinforced seal** is used on pavements where extreme thermal cracking and oxidation has been a problem.




## 9.2. Appendix C- Chapter 2 Methodology

This tool is built up of thousands of lines of code. Therefor it would be impractical to include this here. However, below are some helpful functions that someone could use who is trying to quickly analyse data from a Relational database.

```
/////////////////////////////////////////////////////////////////////////////
function [AllIRISectionIds,IRIextractedData] = LTPP_IRI_Access(FindSIDS)
%LTPP_IRI_ACCESS
%Extracts data from LTPP
%% Set preferences with setdbprefs.

setdbprefs('DataReturnFormat', 'cellarray');
setdbprefs('NullNumberRead', 'NaN');
setdbprefs('NullStringRead', 'null');
%% Make connection to database. Note that the password has been omitted.
%Using ODBC driver.

conn = database('LTPP2', 'admin', '');
```

```
%% Read data from database.

curs = exec(conn, ['SELECT  `10mRoughness`.LwpIRI'...
     ' ,   `10mRoughness`.RwpIRI'...
     ' ,   `10mRoughness`.FinancialYear'...
     ' ,   `10mRoughness`.SECTION_ID'...
     ' ,   `10mRoughness`.LANE_DIRECTION'...
     ' FROM     `10mRoughness` ']);

curs = fetch(curs);
close(curs);

%Assign data to output variable
 IRIextractedData = curs.Data;

%Close database connection.
close(conn);

%Clear variables
clear curs conn

end
////////////////////////////////////////////////////////////////////////////

function [ CAL_SEC_TRAFFIC_DATA ] = CAL_SEC_TRAFFIC_DATA_Access()
%CAL_SEC_TRAFFIC_DATA_ACCESS
%
%Set preferences with setdbprefs.
```

```
setdbprefs('DataReturnFormat', 'cellarray');
setdbprefs('NullNumberRead', 'NaN');
setdbprefs('NullStringRead', 'null');

%Make connection to database.  Note that the password has been omitted.
%Using ODBC driver.
conn = database('LTPP2', 'admin', '');

%Read data from database.
curs = exec(conn, ['SELECT  CAL_SEC_TRAFFIC_DATA.SectionID'...
    ' , CAL_SEC_TRAFFIC_DATA.TMS_AADT'...
    ' , CAL_SEC_TRAFFIC_DATA.Total_pc_heavy'...
    ' FROM  CAL_SEC_TRAFFIC_DATA ']);

curs = fetch(curs);
close(curs);

%Assign data to output variable
CAL_SEC_TRAFFIC_DATA = curs.Data;

%Close database connection.
close(conn);

%Clear variables
clear curs conn

end
```

```
///////////////////////////////////////////////////////////////////////

function [LogMu,LogSigma] = fitLognormalFuntoData(tempList)

%FITLOGNORMALFUNTODATA

%   Try to fit data with a logNorm distribution



try

    pd = fitdist(tempList','Lognormal');

    LogMu = pd.mu;

    LogSigma =pd.sigma;

catch

    display('Can not fit function, LogMu and LogSigma has been set to
NaN')

    LogMu = NaN;

    LogSigma = NaN;



    display(tempList)



end

end



///////////////////////////////////////////////////////////////////////
```

## 9.3. Appendix D Chapter 3

## 9.4. Appendix E Chapter 4 Specific investigation with SBMDM

Standard method

$$\left(\frac{3.96+3.96}{9.2}\right)^4+\left(\frac{6.013+6.013}{13.8}\right)^4+\left(\frac{6.013+6.013}{13.8}\right)^4+\left(\frac{6.013+6.013}{13.8}\right)^4=2.30\ ESA$$

### 9.4.1. Monte Carlo Analysis

| IN PUT PARAMETERS | ESTIMATED MAX | ESTIMATED MIN | SOURCE |
|---|---|---|---|
| **CAMBER** | 3% | 1% | NZ Design Guidelines |
| **DISTANCE BETWEEN WHEELS C** | 2.25 m | 1.75 m | NZTA HRV Factsheet 13a |
| **HEIGHT TO CENTRE OF MASS H** | 2.33m | 1m | (Mueller, De Pont, & Baas, 1999) |
| **MASS PER AXEL** | 8200kg | 5400kg | (NZTA, 2015a) |

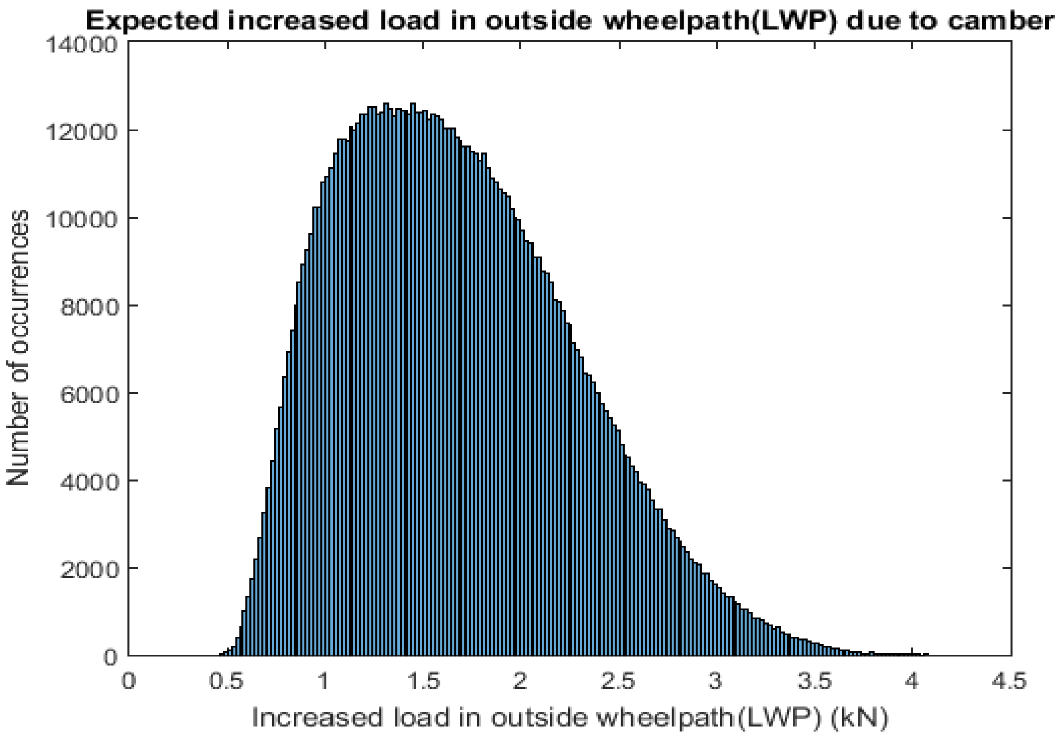



*Figure 42: Increased load in the LWP due to camber on a straight road.*

Using equations from Chapter 4, the effective ESAL for the outer and inner wheel path loads can be calculated for a milk truck on a camber. Full expected distributions can further be estimated if these equation are included in the Monte Carlo analysis.

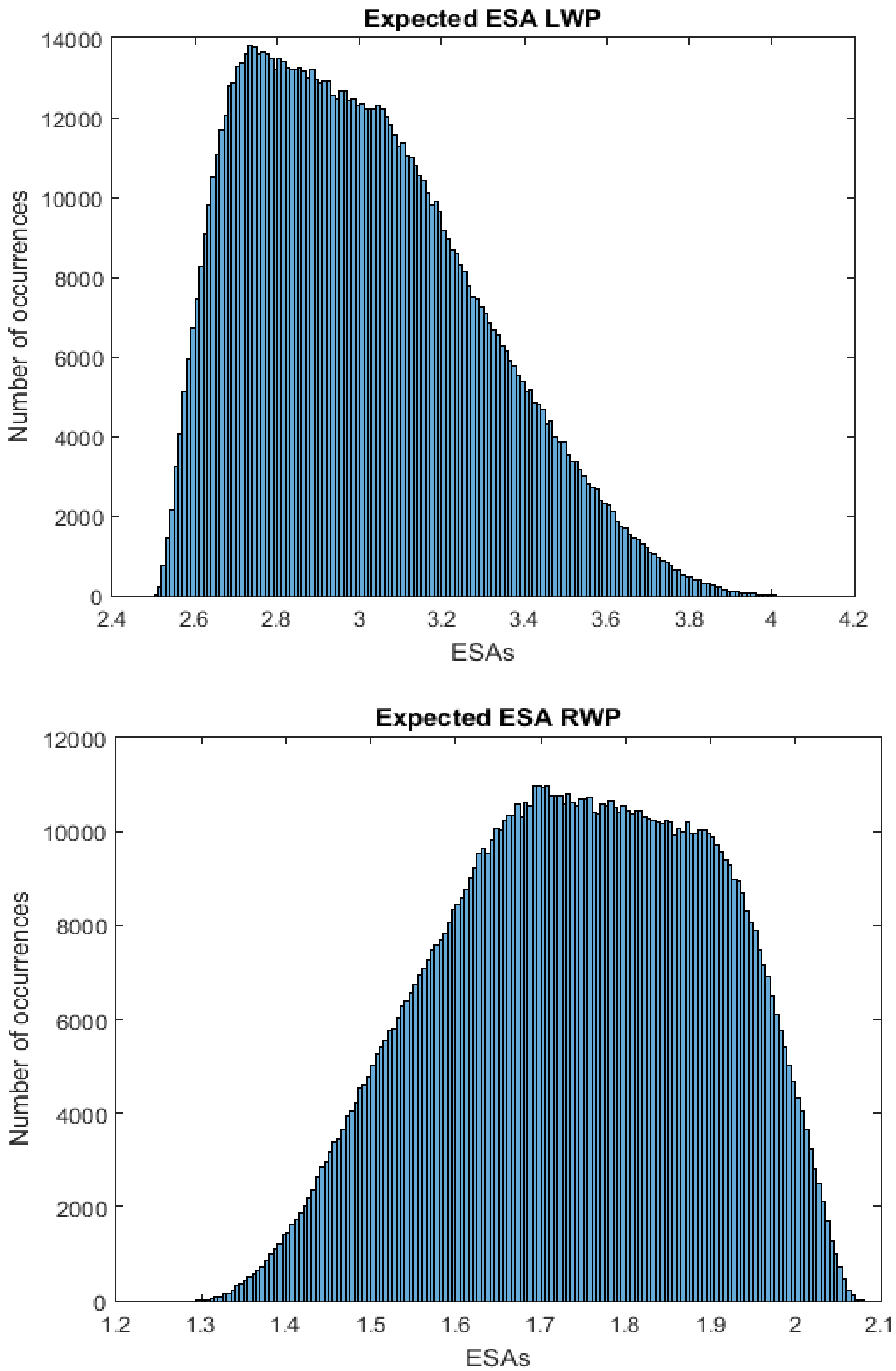



*Figure 43: Outer and inner wheel path expected ESAL*

The figures above shows that when the expected force of the outer wheel is used then the ESAL that should be used in design is 3.01 with a standard deviation of 0.28 per Heavy vehicle. However, when the inside load is used, there is an average ESAL of 1.7 with a standard deviation of 0.16 per heavy vehicle. After conducting a sensitivity analysis, it was found that the relatively flat section at the top of the distributions is most sensitive to the amount of camber on the road ranging from 1% to 3%.

Both these ESAL calculated are significantly different compared to the standard calculation of 2.30 ESAL per heavy vehicle. This result shows that the road would be over designed for the inner wheel path and under designed for the outer wheel path.

*Table 16 : Applying Avrage ESAL results to LTPP section CS-42 & CS-44*

| ESAL TYPE | AV ESAL PER MILK TRUCK | CS -42 AV HV PER DAY | CS-44 AV HV PER DAY | CS-42 AV HV ESAL PER DAY | CS-44 AV HV ESAL PER DAY | CS-42 AV ESAL PER YEAR | CS-43 AV ESAL PER YEAR |
|---|---|---|---|---|---|---|---|
| **STANDARD** | 2.3 | 148.6 | 160 | 341.78 | 368 | 124749.7 | 134320 |
| **OUTWHEEL PATH** | 3.01 | 148.6 | 160 | 447.286 | 481.6 | 163259.4 | 175784 |
| **INNWHEEL PATH** | 1.7 | 148.6 | 160 | 252.62 | 272 | 92206.3 | 99280 |

## T-Test Analysis

In this case, roughly 120 data points were used for each group, and the Alpha level is set to 0.05 or 5%. One of the key assumptions of the T-test is that the data points of each group are normally distributed. When the distributions of were inspected, it became apparent that this was not always the case. Section SC-42 showed that in the years the recorded data is normally distributed however the data showed much higher positive skewness in later years. SC-44 showed some skewness however not as apparent. To compensate for this, a Log base 10 transformations of the data was competed. This solved the problem and made all skewness values fall between the rule of thumb -1 to +1 skewness. For completion both the non-transformed data and transformed data was examined using the independent T-test as shown in tables 17 and 18.

*Table 17: Results from competing T-test on sections CS-42 and CS-44. T-test result of 1 indicated that we could reject Ho.*

| CS-42 NORTH CANTERBURY | | | | | CS-44 SOUTH CANTERBURY | | | |
|---|---|---|---|---|---|---|---|---|
| **YEAR** | T test result | P Value | LWP M (mm) | RWP M (mm) | T test result | P Value | LWP M (mm) | RWP M (mm) |
| **2002** | 1 | <0.01 | 6.57 | 2.87 | 1 | <0.01 | 4.13 | 3.09 |
| **2003** | 1 | <0.01 | 6.06 | 2.62 | 1 | <0.01 | 4.09 | 3.22 |
| **2004** | 1 | <0.01 | 6.89 | 2.51 | 1 | <0.01 | 4.60 | 3.38 |
| **2005** | 1 | <0.01 | 6.69 | 2.48 | 1 | <0.01 | 4.37 | 3.25 |
| **2006** | 1 | <0.01 | 7.32 | 2.54 | 1 | <0.01 | 4.59 | 3.24 |
| **2007** | 1 | <0.01 | 6.83 | 2.32 | 1 | <0.01 | 4.93 | 3.06 |
| **2008** | 1 | <0.01 | 7.68 | 2.71 | 1 | <0.01 | 5.34 | 3.07 |
| **2009** | 1 | <0.01 | 7.46 | 2.88 | 1 | <0.01 | 5.57 | 3.09 |
| **2010** | 1 | <0.01 | 7.54 | 2.98 | 1 | <0.01 | 5.53 | 3.16 |
| **2011** | 1 | <0.01 | 8.67 | 3.56 | 1 | <0.01 | 6.26 | 3.36 |
| **2012** | 1 | <0.01 | 9.55 | 3.73 | 1 | <0.01 | 6.38 | 3.29 |
| **2013** | 1 | <0.01 | 10.58 | 3.80 | 1 | <0.01 | 6.62 | 3.36 |
| **2014** | 1 | <0.01 | 10.58 | 3.99 | 1 | <0.01 | 7.55 | 3.33 |

*Table 18: Log transformation Independent T-Test Results. T-test result of 1 indicated that we could reject Ho.*

| | CS-42 NORTH CANTERBURY | | | | CS-44 SOUTH CANTERBURY | | | |
|---|---|---|---|---|---|---|---|---|
| **YEAR** | T test result | P Value | LWP M (mm) | RWP M (mm) | T test result | P Value | LWP M (mm) | RWP M (mm) |
| **2002** | 1 | <0.01 | 6.57 | 2.87 | 1 | <0.01 | 4.13 | 3.09 |
| **2003** | 1 | <0.01 | 6.06 | 2.62 | 1 | <0.03 | 4.09 | 3.22 |
| **2004** | 1 | <0.01 | 6.89 | 2.51 | 1 | <0.01 | 4.60 | 3.38 |
| **2005** | 1 | <0.01 | 6.69 | 2.48 | 1 | <0.01 | 4.37 | 3.25 |
| **2006** | 1 | <0.01 | 7.32 | 2.54 | 1 | <0.01 | 4.59 | 3.24 |
| **2007** | 1 | <0.01 | 6.83 | 2.32 | 1 | <0.01 | 4.93 | 3.06 |
| **2008** | 1 | <0.01 | 7.68 | 2.71 | 1 | <0.01 | 5.34 | 3.07 |
| **2009** | 1 | <0.01 | 7.46 | 2.88 | 1 | <0.01 | 5.57 | 3.09 |
| **2010** | 1 | <0.01 | 7.54 | 2.98 | 1 | <0.01 | 5.53 | 3.16 |
| **2011** | 1 | <0.01 | 8.65 | 3.37 | 1 | <0.01 | 6.26 | 3.36 |
| **2012** | 1 | <0.01 | 9.85 | 3.00 | 1 | <0.01 | 6.38 | 3.29 |
| **2013** | 1 | <0.01 | 10.55 | 3.54 | 1 | <0.01 | 6.62 | 3.36 |
| **2014** | 1 | <0.01 | 10.80 | 3.63 | 1 | <0.01 | 7.55 | 3.33 |

From the result of the independent T-test, it was found that t the null hypothesis could be rejected at a significance level of 5 % for both the non-and transformed data. It can also be noted that all P values are very small thus there is an insignificant probability that this difference between mean values could occur purely by chance.